BOOK OF ABSTRACTS

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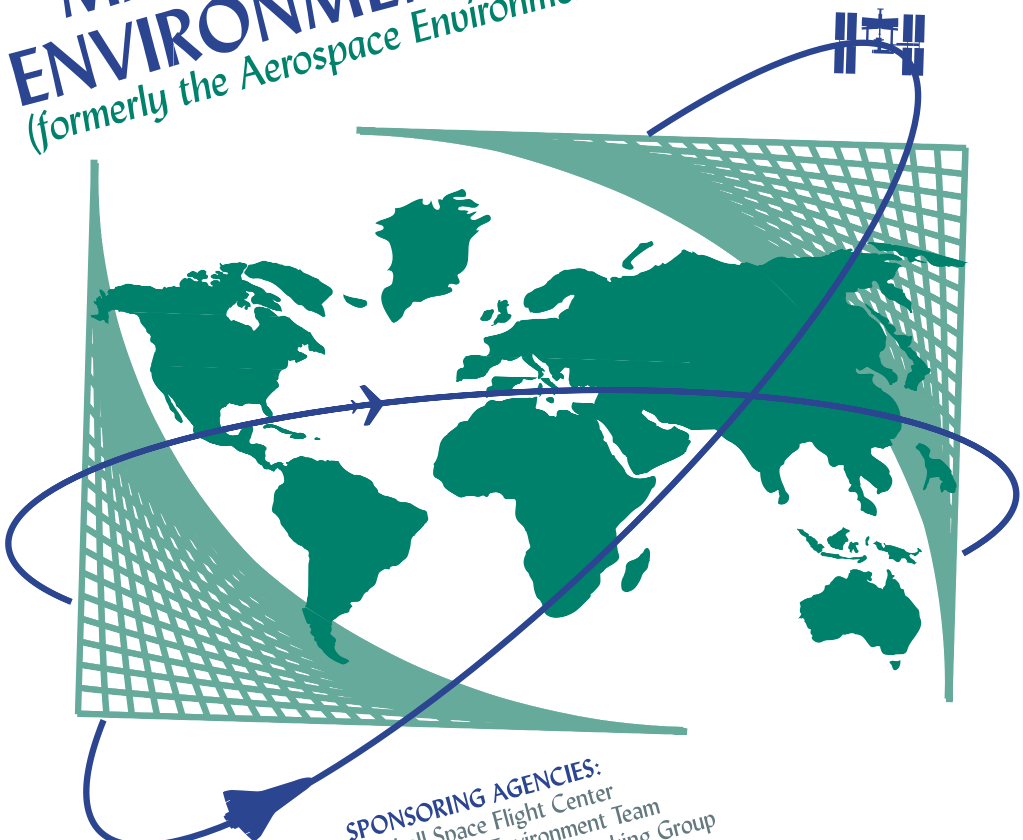
(formerly the Aerospace Environmental Technology Conference)



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The Next Generation of Enhanced Environmentally Preferred Cleaning Solvents

JOHN D. WEIR

Northrop Grumman
M/S D08-001
Bethpage, NY 11714 USA
Phone: 516-575-5422
Fax: 516-575-6672
E-mail: WEIRJO@MAIL.NORTHGRUM.COM

Joanne S. McLaughlin
Northrop Grumman
M/S 30/9C30/GK
Pico Rivera, CA 90660 USA
Phone: 562-948-0140
Fax: 562-948-8870

Richard Doria
Northrop Grumman
5000 U.S. 1 North
P.O. Drawer 34470140
St. Augustine, FL 32085-3447 USA
Phone: 904-825-3828
Fax: 904-825-6156

A new class of proprietary, environmentally preferred cleaning solvents has been developed by Northrop Grumman for cleaning aircraft parts before painting, bonding, and sealing. These novel solvents have been found to be superior with respect to the more conventionally formulated compliant solvents currently on the market, as well as the older and non-compliant solvents such as methyl ethyl ketone (MEK), 1,1,1 trichloroethane (TCA), or trichloroethylene (TCE). After cleaning aircraft parts, the Northrop Grumman solvents have been shown to impart improved substrate corrosion resistance and adhesion for painting, sealing, and adhesive bonding applications.

The Northrop Grumman proprietary cleaning solvents are free of Hazardous Air Pollutants (HAPs) and ozone depleting substances (ODSs). In addition, they are formulated below 45 mm of mercury in vapor pressure, allowing for compliance with the National Emissions Standard for Hazardous Air Pollutants and do not create, of themselves, a hazardous waste when used as a wipe solvent.

This paper will review the selected test protocol and associated test data generated to validate these newly formulated solvents for cleaning applications before painting, bonding, and sealing. The test protocol and data to be discussed include both wet and dry tape adhesion, water resistance, salt fog corrosion resistance, filiform corrosion resistance, peel strengths, and lap shear validation of adhesive bond strengths.

Nonflammable, Nonaqueous, Low Atmospheric Impact, High-Performance Cleaning Solvents

PATRICK M. DHOOGE, Suzanne M. Glass, and Jonathan S. Nimitz

Environmental Technology and Education Center (ETEC)
4500-B Hawkins St., NE
Albuquerque, NM 87109-4517 USA
Phone: 505-345-2707
Fax: 505-345-4884
E-mail: pdhooge@etec-nm.com
jnimitz@aol.com

The success of many aerospace operations depends critically on the final cleanliness of equipment surfaces. This is particularly true for propellant and life support systems, with oxygen systems being some of the most sensitive to contaminants. CFC-113 has traditionally been used to clean oxygen systems, for other critical cleaning applications, and for cleanliness verification analysis. However, environmental regulations have dictated the phaseout of ozone-depleting solvents such as CFC-113 and 1,1,1-trichloroethane. CFC-113 is now difficult to obtain and expensive. As a result, many new cleaning solvents and techniques have recently appeared. Some applications are cost-effective; however, other new methods are also expensive and give incomplete cleaning or leave residues that may compromise the reliability of aerospace systems.

ETEC has developed a new high-performance solvent based on an iodofluorocarbon (IFC) in a project sponsored by the Air Force Research Laboratories. IFCs have zero ozone-depletion potential (ODP), extremely low global warming potential (GWP), excellent physical properties and cleaning ability, a toxicity comparable to commonly used chlorinated solvents, good compatibility, and good thermal stability.

This paper reviews the physical properties, cleaning abilities, toxicity, flammability, compatibility, environmental impacts, and cost of the solvent toxicity tests. Worker exposure risk assessment shows that the solvent is not carcinogenic by the Ames test, not clastogenic by the human lymphocyte test, has low chronic inhalation toxicity (all test rats survived 10,000 ppm exposure, 6 hr/day for 28 days), and in general appears to be comparable with 1,1,1-trichloroethane in exposure hazard. The atmospheric lifetime of the IFC is approximately 2 days, giving essentially zero ODP, and has a GWP of about 6, relative to CO_2 with a 100-year time horizon. Ikon® Solvent P can easily be re-purified for reuse by distillation. Ikon® Solvent P has no flash point in air and passes the liquid oxygen compatibility impact test at 65 ft-lb. Its autogenous ignition temperature in 100% oxygen at 13.8 Mpa (2000 psia) was measured as 171 - 175°C.

Cleaning test results show good-to-excellent cleaning ability on a wide range of soils and substrates. The cleaning ability of the new solvents was comparable to, and in some instances better than, CFC-113. Ikon® Solvent P appears to be superior to CFC-113 in removing fluorinated greases, a problematic soil in oxygen systems. As Ikon® Solvent P has no C-H bonds, it can substitute for CFC-113 in chemical analyses such as extractable hydrocarbon IR analysis.

Aerospace Applications for AK-225

KENROH KITAMURA and Masaaki Tsuzaki

Technology and Process Development Center
Performance Chemicals General Division
Asahi Glass Co., Ltd.
10, Goikaigan, Ichihara-shi, Chiba 290-8566, Japan
Phone: +81-436-23-3151
Fax: +81-436-23-3164

Stephen D. Stagliano
AGA Chemicals, Inc.
2201 Water Ridge Parkway, Suite 400,
Charlotte, NC 28217 USA
Phone: 704-357-3631
Fax: 704-357-6308
E-mail: Steve_Stagliano@chemicals.asahiglass.com

AK-225 products are viable environmental alternatives to CFC-113, perfluorocarbons (PFCs), and other hydrochlorofluorocarbons with high oxygen-depleting potential (ODP) values, such as HCFC-141b, in many applications. Asahi Glass has commercialized AK-225 as a mixture of two isomers, *i.e.,* HCFC-225ca ($CF_3CF_2CHCl_2$) and HCFC-225cb ($CClF_2CF_2CHClF$); AK-225G, *i.e.,* HCFC-225cb; and many azeotrope-like mixtures and blends. AK-225 products are very similar to CFC-113 in physical properties, material compatibilities, and cleaning performance and are widely used in precision cleaning and as a carrier solvent of fluorinated lubricants and silicones.

In this paper, fundamental properties and material compatibility of AK-225 products and their applications, especially for aerospace related industries such as bearings, precision parts, and PCBs, will be presented. Typical cleaning procedures of AK-225, its toxicological data, and the status of regulations will be also described.

HFEs in the Aerospace Industry: A Logical Alternative to CFCs and Other Halogenated Cleaning Solvents

DAVID A. HESSELROTH

3M Company
Performance Materials Division
St. Paul, MN 55144 USA
Phone: 651-736-6191
E-mail: dahesselroth@mmm.com

Hydrofluoroethers (HFEs) cover a wide range of cleaning strengths and compatibilities. The neat HFEs are among the best solvent alternatives in terms of environmental properties. They are volatile organic compound (VOC) exempt, are not oxygen depleting chemicals, and have one of the best global warming potentials. The uses of HFEs cover more than cleaning. Since their introduction, they have been used successfully in many applications.

Halogenated solvents have been used in high-value precision applications for many years. The elimination of chlorinated fluorocarbons (CFCs) has forced development of new solvents in many applications. Sometimes, it has taken many solvents to do what one CFC did. HFEs can substitute for the unavailable CFC in many applications. The HFEs have a good balance of material compatibility and excellent electronic properties for long-term contact with sensitive components. Their high density, low surface tension, and low viscosity make them excellent for particulate removal. These attributes are also beneficial in applications that require fluids with good heat transfer properties. The stability of the HFEs enables them to be used in closed systems for long periods of time, while having a relatively short atmospheric lifetime for use in emissive applications. The HFEs have favorable toxicological properties. They are commonly used in applications where workers might be exposed to the chemicals. They are used in vapor degreasers, wipe and spray cleaners, and flush solvents for tubes and hoses. Blending the HFEs with other solvents, such as mixtures or azeotropes, can yield enhanced solvent power while maintaining the reduced toxicological and environmental problems that might exist with the other material. The HFEs are also used in constant temperature baths for electronic testing, closed-loop cooling systems, and as solvents for electronic conformal coatings. They have also been found to be effective machining and forming oils for certain applications, reducing or eliminating the need for cleaning. An overview of the properties, applications and testing will be covered.

Elimination of MEK and Lacquer Thinner in Department of Defense Painting Operations

JOSEPH A. LUCAS

Inland Technology Incorporated
401 East 27th Street
Tacoma, WA 98421 USA
Phone: 800-552-3100
Fax: 253-593-8749
E-mail: inland@inlandtech.com

Eric Lethe
Inland Technology Incorporated
401 East 27th Street
Tacoma, WA 98421 USA
Phone: 253-383-1177
Fax: 253-593-8749
E-mail: inland@inlandtech.com

Inland Technology is a research and development company devoted to the development and validation of environmentally compliant chemistries to replace problematic industrial solvents such as ozone depleting substances, hazardous air pollutants, and volatile organic compounds (VOCs). Identified by the National Defense Center for Environmental Excellence as a research center supporting the defense community, Inland Technology has been in the forefront of solvent substitution efforts in both the aerospace community and in each branch of the military service. As a result of these efforts, we have developed many technical case studies and success stories regarding successful pollution prevention via solvent substitution.

This paper will touch briefly on the technical issues involved in solvent substitution. It will also address a systematic protocol that can be employed to avoid many of the pitfalls inherent in solvent substitution activities. It will then focus on the process of reducing MEK and lacquer thinner usages in painting operations through solvent substitution.

Painting operations at aerospace industrial and Department of Defense (DoD) facilities create large and problematic waste streams, as well as major emissions of hazardous air pollutants and VOCs. Some emissions and waste streams originate in the paint being used and are being addressed by changes in paint formulas. However, an excess of 50% waste and emissions generated in painting operations originates from the use of methyl ethyl ketone (MEK) and lacquer thinner for surface preparation activities and in paint equipment cleanup. The successful elimination of MEK and lacquer thinner for these painting-associated activities would assist these facilities in meeting the aerospace National Emissions Standard for Hazardous Air Pollutants requirements and would also reduce the generation of hazardous waste and emissions of VOCs from these facilities.

This paper will cover case studies of successful MEK and lacquer thinner replacement in painting operations at civilian industry and DoD installations, detailing the substitution process and the resulting chemistry and discussing equipment validation procedures, work practice changes, and training required to make each project a success. In each case study, the result was a replacement process and chemistry more environmentally responsible and less regulated than the original process. Also, each substitution process resulted in demonstrable cost avoidance.

Lightweight Multi-layer Structural Materials

H.H. LEGNER and W.T. Laughlin

Physical Sciences, Inc.
20 New England Business Center
Andover, MA 01810 USA
Phone: 978-689-0003 or 978-983-2234
Fax: 978-689-3232
E-mail: legner@psicorp.com

V. Di Cristina
ThermoPhysical Sciences

D. Marshall and R. Singler
Textron Systems

A new lightweight composite material with combined structural and thermal protection capability has been developed for both air vehicle and spacecraft application. The basic concept consists of the integration of a high-density outer layer with a low-density foam core, using stitching loops to integrate the material three-dimensionally. The layers are chemically bonded and mechanically linked. The generalization of this technique to integrated structural materials with two high-density face plates sandwiching the low-density inner layer provides an entirely new approach to fabricating cost-effective aero-shell and spacecraft structural materials. These materials have been evaluated structurally, as well as thermally in arc-jet and laser tests. Thermal insulation performance exceeds that of standard heat protection materials. Measured compressive and bending strengths have shown substantial residual load-carrying capabilities. In addition, damage tolerance and crush strength properties have been demonstrated to be superior to comparable honeycomb structures.

Asbestos-Free Insulation Development for the RSRM

LARRY D. ALLRED

Thiokol Propulsion
P.O. Box 707, M/S LC0
Brigham City, UT 84302 USA
Phone: 435-863-6692
E-mail: allreld@thiokol.com

Asbestos has been used for many years as an ablation inhibitor in insulating materials. It has been a constituent of the nitrile butyl rubber insulation used to protect the steel case of the Reusable Solid Rocket Motor (RSRM) since its inception. Asbestos is a serious health hazard. Its use could be curtailed with little warning, which could affect production of the RSRM. A development program was initiated in 1986, and numerous Asbestos-Free (AF) insulation candidates were evaluated using 70-lb charge motors and Modified NASA (MNASA) motors. Kevlar-filled (KF) Ethylene Propylene Diene Monomer (EPDM) insulation was selected for use in several solid rocket motors. The formulation was modified for structural and ablation issues, and a 7% KF EPDM was developed as the primary insulation for the AF RSRM.

The first demonstration of AF insulation on an RSRM used both 7% and 11% KF EPDM in the aft dome region of Flight Simulation Motor-5 (FSM-5). Following this demonstration, the AF program was cancelled until 1997, when a more complete demonstration of the AF design was approved for FSM-8.

Since that time, numerous design issues have been worked. For example, processing problems were resolved, full-scale process simulation articles were built, and multiple components of FSM-8 were manufactured.

Two major problems had to be overcome in developing the AF design. First, bondline corrosion, which occurred in the double-cured region of the aft dome, had to be eliminated. Second, KF EPDM created high levels of electrostatic energy (ESE), which did not dissipate from the insulation surface. An uncontrolled discharge of this surface energy during many phases of production would be a serious safety concern. Numerous processing changes were implemented, and a conductive paint was developed to protect exposed external insulation surfaces from generating ESE.

Special internal instrumentation was incorporated into this motor to record real-time internal motor environment data. These data included inhibitor insulation erosion rates, internal thermal environments, and J-joint dynamics. The FSM-8 static test was successfully conducted in February 2000, and valuable data were obtained to characterize this AF insulation.

Aerogel Projects Ongoing in MSFC's Engineering Directorate

DAVID SHULAR

Marshall Space Flight Center/ED25
Huntsville, AL 35812 USA
Phone: 256-544-8734
Fax: 256-544-0800
E-mail: David.A.Shular@msfc.nasa.gov

Gweneth Smithers
Marshall Space Flight Center/ED34
Huntsville, AL 35812 USA
Phone: 256-544-0282
Fax: 256-544-7255
E-mail: Gweneth.smithers@msfc.nasa.gov

Joel Plawsky
Rensselaer Polytechnic Institute
Troy, NY 12180-3590 USA

Aerogel materials are being considered at MSFC for a broad range of applications. Successful application begins with understanding and improving the materials themselves. This includes the processes used to make them. After a review of technical literature, we decided to pursue manufacturing avenues that eliminate the need for autoclaving and supercritical drying. At the same time, we recognized the value of the autoclave technique for certain aerogel applications and the need to remain involved with developments in this area. Our study of aerogel material has taken us into partnerships with academia, industry, and other NASA Centers. This paper describes aerogel projects underway in MSFC's Engineering Directorate and future directions envisioned.

Electroactive Polymers as Artificial Muscles – Reality and Challenges

YOSEPH BAR-COHEN

NDEAA Technologies
Jet Propulsion Laboratory/Caltech
4800 Oak Grove Drive, M/S 82-105
Pasadena, CA 91109-8099 USA
Phone: 818-354-2610
Fax: 818-393-3254
E-mail: yosi@jpl.nasa.gov

For many years, electroactive polymers (EAPs) received relatively little attention because of the small number of available materials and their limited actuation capability. The recent emergence of EAP materials with large displacement response changed the paradigm of these materials and their potential capability. The main attractive characteristic of EAPs is their operational similarity to biological muscles, particularly their resilience and ability to induce large actuation strains. Researchers at JPL, in collaboration with other investigators in the U.S. and Japan, are developing unique robotic components and miniature devices using EAP as actuators to enable new capabilities.

In recognition of the need for international cooperation among the developers, users, and potential sponsors, an SPIE (International Society for Optical Engineering) Conference was organized for the first time in March 1-2, 1999, in Newport Beach, California. This conference was the largest ever on EAP, and it marked an important milestone, turning the spotlight onto these emerging materials and their potential. Current materials are capable of inducing large displacement but at low force.

A challenge was posed to the EAP science and engineering community to develop a robotic hand actuated by EAP that is able to win against a human in an arm wrestling match. Progress toward this goal will lead to great benefits in many technology areas, including medicine and robotics. In this presentation, the capabilities, challenges, and potentials of state-of-the-art EAP materials for miniature robotics and other applications will be reviewed.

Overview of the National Center for Advanced Manufacturing

JOHN VICKERS

Marshall Space Flight Center/ED34
Huntsville, AL 35812 USA
Phone: 256-544-3581
Fax: 256-544-7255
E-mail: John.H.Vickers@msfc.nasa.gov

In late 1998, NASA established the National Center for Advanced Manufacturing (NCAM) to be administered under the direction of the Office of the Chief Technologist and through Marshall Space Flight Center. The NCAM was chartered to address the research and technology development needs for manufacturing future space transportation systems, enabling NASA to meet the requirements of the systems successfully. Partnerships between NASA, other federal government agencies, state governments, industry, and academia are being utilized to effect a cultural change in the manufacturing work to an intelligent, collaborative environment. The NCAM is establishing and facilitating these partnerships, thereby strengthening the competitiveness of the U.S. in the aerospace marketplace through advanced manufacturing developments.

Advanced Engineering Environments – Implications for Aerospace Manufacturing

DALE THOMAS

Marshall Space Flight Center/VS10
Huntsville, Alabama 35812 USA
Phone: 256-544-1180
Fax: 256-544-8250
E-mail: Dale.Thomas@msfc.nasa.gov

Significant challenges face today's aerospace industry. Global competition, more complex products, geographically distributed design teams, demands for lower cost, higher reliability and safer vehicles, and the need to incorporate the latest technologies more quickly — all face the developer of aerospace systems. New information technologies offer promising opportunities to develop advanced engineering environments to meet these challenges. Significant advances in the state-of-the-art of aerospace engineering practice are envisioned in the areas of engineering design and analytical tools, cost and risk tools, collaborative engineering, and high-fidelity simulations early in the development cycle. These advances will enable modeling and simulation of manufacturing methods, which in turn will allow manufacturing considerations to be included much earlier in the system development cycle. Significant cost savings, increased quality, and decreased manufacturing cycle time are expected to result.

This paper will give an overview of NASA's Intelligent Synthesis Environment, the agency initiative to develop an advanced engineering environment with a focus on the anticipated benefits in aerospace manufacturing.

Composite Manufacturing for Space Launch Vehicles

DONNA Y. KNEZEVICH

Lockheed Martin Space Systems/D-4800
P.O. Box 29304
New Orleans, LA 70189 USA
Phone: 504-257-2445
E-mail: donna.y.knezevich@maf.nasa.gov

Composite materials offer a large potential for performance increase and weight reduction over metallic components for advanced launch vehicles. Building composite hardware for large high-efficiency launch vehicles is one of the most demanding engineering challenges from the aspects of materials science, structure, and manufacturing. Modern launch vehicles require robust, durable, and reliable components capable of operating in cryogenic, high-pressure, and high-temperature environments, while in contact with highly volatile oxidizers and fuels.

Lockheed Martin Space Systems Company, Michoud Operations, has developed critical technologies for this effort by building, testing, and flight qualifying composite hardware for launch vehicle applications for numerous projects, such as the Space Shuttle, X-33, X-34, and the A2100 Satellite. Composite hardware built and tested by Lockheed Martin Space Systems Company includes high-temperature vehicle fairings and nosecones, launch vehicle intertank skirts, high-pressure cryogenic helium tanks, cryogenic liquid hydrogen and liquid oxygen tanks, feedlines, and tank coverplates. Composite manufacturing for space launch vehicles will soon be enhanced by activation of the National Center for Advanced Manufacturing (NCAM). Located at Michoud, NCAM will partner government, industry, and academia and bring on line fiber placement and autoclave capabilities that are required for production of large composite structures.

Education, Industry, and Government Partnerships Expanding Education and Meeting Workforce Challenges

JAMES E. SWINDELL

Calhoun Community College
P.O. Box 2216
Decatur, AL 35609-2216 USA
Phone: 256-306-2539
E-mail: jes@calhoun.cc.al.us

DONNA C. BASS

Alabama Industrial Development Training
P.O. Box 1763
Decatur, AL 35609-1763
Phone: 256-306-2517
Fax: 256-306-2589
E-mail: dbass@aidt.edu

WILLIAM R. REYNOLDS

Boeing, Delta IV Operations
100 Decatur Way
Trinity, AL 35673
Phone: 256-432-1155
Fax: 256-432-1554
E-mail: William.Reynolds2@HSV.Boeing.com

Calhoun Community College, The Boeing Company, Alabama Industrial Development Training, and the Morgan County Economic Development Association have collaborated to develop a skilled workforce for the $450M Delta IV factory in Decatur, Alabama. This program will present an overview of trends in the technical workforce, describe the key factors in Boeing's decision to locate in North Alabama, and the role of each partner in developing a workforce plan to meet Boeing's employment, staffing, and training needs. The presentation will also address how this initiative is integrated into the College's overall plan to develop a Technology Park providing advanced technology training programs, technology demonstration and transfer, and regional economic development support to ensure regional and national economic competitiveness.

Laser Cladding/Glazing as a Surface Coating Alternative

ROB HULL

Anteon Corporation
5100 Springfield Pike, Suite 509
Dayton, OH 45431 USA
Phone: 937-252-3132 x3009
Fax: 937-252-0418
E-mail: rhull@anteon.com

Chuck Woods
Global Manufacturing Solutions
720 Mound Ave, B-3
Miamisburg, OH 45343 USA
Phone: 937-865-5039
Fax: 937-865-4749
E-mail: cwoods@globalms.com

Dave Firsich
Inorganic Specialists
720 Mound Ave, COS-327
Miamisburg, OH 45343 USA
Phone: 937-865-4491
Fax: 937-865-3680
E-mail: firsich@coax.net

John Eric
AFRL/MLPJ
3005 P Street, Suite 1
Wright-Patterson Air Force Base, OH 45433 USA
Phone: 937-255-2334 x3165
Fax: 937-255-1128
E-mail: john.eric@ml.afrl.af.mil

Increasing environmental regulations and rising waste disposal costs are driving the need for economic chrome plating replacement technologies. This paper summarizes one of several chrome replacement research and development programs funded by the Air Force Pollution Prevention Office. This work focuses on two laser-based coating processes – laser cladding and laser glazing – for the application of a thick (5 to 25 mil) uniform coating with similar, if not superior, mechanical performance to that of hard (wet) chrome plating. All experiments were performed using a flattop, continuous wave carbon dioxide laser, operating at 10.6 microns.

This paper describes the laser cladding and glazing techniques, the processing parameters developed, and the mechanical performance of the resultant coatings. Emphasis will be placed on the laser glazing technique developed under this effort. The technique uses the laser's rapid surface heating effect to melt, re-flow, and consolidate protective coatings deposited by any type of thermal spray technique (in this case, a flame-spray coating system). Post flame-spray treatment using laser glazing transformed an economical but porous coating into a uniform, pore-free coating with performance characteristics superior to that of chrome. Materials characterization and mechanical property test results are discussed.

Testing of Environmentally Preferable Aluminum Pretreatments and Coating Systems for Use on Space Shuttle Solid Rocket Boosters (SRBs)

CATHERINE CLAYTON

United Space Alliance, Inc.
SRB Element
8550 Astronaut Boulevard
Cape Canaveral, FL 32920-4304 USA
Phone: 321-853-0523
Fax: 321-853-7945
E-mail: Catherine.Clayton-1@kmail.ksc.nasa.gov

Lee Zook and Randy Raley
United Space Alliance, Inc.
SRB Element
8550 Astronaut Boulevard
Cape Canaveral, FL 32920-4304 USA

Historically, the SRBs have undergone a chromate conversion coating before the protective finish application. After conversion coating, an organic paint system consisting of a chromated epoxy primer and polyurethane topcoat are applied. An overall systems approach was selected to reduce waste generation from the coatings application and removal processes. While the most obvious waste reduction opportunity involved elimination of the chromate conversion coating, several other coating system configurations were explored in an attempt to reduce total waste. This paper will discuss the use of a systems view to reduce waste generation from the coating process and will present the results of the qualification testing of nonchromated aluminum pretreatments and alternate coating system configurations.

Trivalent Chromium/Organically Modified Silicate Composite Coatings for Corrosion Protection of Aluminum Alloys

EDWARD KNOBBE

Center for Aircraft Support and Infrastructure
003 Life Sciences East
Oklahoma State University
Stillwater, OK 74078 USA
Phone: 405-744-9994
Fax: 405-744-7673
E-mail: knobbe@okstate.edu

Elvira Stesikova, Tammy Metroke, and Olga Kachurina
Oklahoma State University
Stillwater, OK 74078 USA
E-mail: stesiko@okstate.edu

Organically modified silicate (ORMOSIL) materials containing organic/inorganic phases have been shown to form mechanically stable protective coatings on aluminum alloy (AA) substrates. Improved corrosion resistance is observed when AA surfaces receive a trivalent chromium solution rinse before the ORMOSIL film application. These composite coatings, combining conversion and hybrid ORMOSIL films, are environmentally compliant and may be used to replace environmentally hazardous, hexavalent chromium treatments. The 168-hour, 2000-hour salt-fog and filiform tests reveal that composite coatings exhibit very good corrosion protection of 2024-T3 aluminum alloys. Superior corrosion protection of AA coated with the composite films, as compared to that of bare and chromate-treated AA, was also demonstrated by electrochemical corrosion studies involving acquisition of polarization curves and measurement of corrosion potential and corrosion resistance.

HVOF Thermal Spray Coating as an Alternative to Hard Chrome Plating on Military Aircraft

BRUCE D. SARTWELL

Naval Research Laboratory, Code 6170
4555 Overlook Avenue
Washington, DC 20375 USA
Phone: 202-767-0722
Fax: 202-767-3321
E-mail: sartwell@nrl.navy.mil

This paper will describe a program to qualify tungsten carbide/cobalt (WC/Co) and tungsten carbide/cobalt chromium (WC/CoCr) coatings deposited by the high-velocity oxygen-fuel (HVOF) thermal spray technique as replacements for hard chrome plating. Hard chrome plating is currently being used in both the manufacture and repair of different types of military aircraft components. The Hard Chrome Alternatives Team (HCAT), formed by the Department of Defense (DoD), is executing separate projects related to chrome replacement on landing gear, propeller hubs, hydraulic actuators, helicopter dynamic components, and gas turbine engine components. The HCAT consists of representatives from military aircraft repair depots, aircraft manufacturers, and technical experts in the coatings field. The HCAT is partnering with the DoD Joint Group on Pollution Prevention (JG-PP) to execute all of the projects with the exception of the project on gas turbine engine components. For this project, the HCAT is partnering with the DoD Propulsion Environmental Working Group (PEWG). Joint test protocols have been prepared in each area, describing the required materials and component testing for qualification of the HVOF coatings. These protocols generally include fatigue, wear, and corrosion testing and limited operational evaluations of actual coated components. Results for the materials and operational testing in the landing gear project will be presented. These include fatigue testing of 75- and 250-micrometer-thick HVOF and chrome coatings deposited onto 4340, 300M, and Aermet 100 high-strength steels. In general, there was little or no reduction in fatigue strength for the HVOF-coated materials and significant loss of fatigue strength for the chrome-coated materials. Information related to the impact of HVOF coatings on overall costs of aircraft maintenance activities will also be presented.

The Use of Ion Vapor Deposited (IVD) Aluminum for the Space Shuttle Solid Rocker Booster

HOWARD NOVAK, Bill Imre, and Randy Raley

United Space Alliance, Inc.
Attn: H.L. Novak, M/S: USK-864
8550 Astronaut Boulevard
Cape Canaveral, FL 32920-4304 USA
Phone: 321-867-7052
Fax: 321-867-9904
E-mail: novakh@usasrb.ksc.nasa.gov

United Space Alliance's SRB Element Materials & Processes and Engineering Departments had recommended the application and evaluation of IVD aluminum to SRB hardware for corrosion protection and elimination of hazardous materials and processes, such as cadmium plating and chromated primer paint. IVD is an environmentally friendly process that has no volatile organic compounds or hazardous waste residues. It lends itself to use with hardware exposed to corrosive seacoast environments, such as those found at Kennedy Space Center, Cape Canaveral Air Station, and Patrick Air Force Base, Florida. In the past, an Engineering Change Request was approved by the MSFC SRB Program Office for the first application of IVD aluminum on Ground Support Equipment (GSE). The lifting apparatus, initially coated with cadmium plating for corrosion protection, was stripped and successfully recoated with IVD aluminum when it was determined that the cadmium plating no longer protected the GSE from corrosion. Since then and after completion of a significant test program, an Engineering Change Proposal was approved by the MSFC SRB Program Office for the first flight application of the IVD aluminum process on the Drogue Parachute Ratchet Assembly. This paper describes the nature of the IVD aluminum process, its application to selected SRB flight hardware candidates, a performance evaluation, and recommendations for potential future applications.

High-Temperature Material Performance Testing Using Continuous Wave Carbon Dioxide Lasers

TIMOTHY JOHNSON

Anteon Corporation
5100 Springfield Pike, Suite 509
Dayton, OH 45431 USA
Phone: 937-252-3132 x3016
Fax: 937-252-0418
E-mail: tjohnson@anteon.com

A key aspect of material development is the ability to simulate the anticipated real-world application in a laboratory environment. Using continuous wave carbon dioxide (CO_2) lasers to simulate anticipated heat loads on high-temperature materials is an efficient, cost-effective tool for evaluating the performance of aerospace materials. This paper describes the use of high-power lasers to simulate heat loads for evaluating the performance of aerospace materials. The use of continuous wave lasers as radiant heating sources has many advantages in the evaluation of high-temperature materials. This presentation will discuss one application that resulted in superior response data at significant savings to NASA.

Over 2,000 material performance tests have been conducted for NASA at the Laser Hardened Material Evaluation Laboratory (LHMEL) on many of the internal ablative insulations used on the Reusable Solid Rocket Motor (RSRM). The testing has encompassed incident heat flux rates ranging from 25 to 5,000 W/cm^2 and a recorded maximum surface temperature in excess of 7000 °F. The LHMEL's high-power CO_2 lasers have characteristics that make them unique. Their two foremost characteristics are the magnitude of power output and the flat spatial profile or "top hat" of the beams they produce. LHMEL's continuous wave CO_2 lasers deliver up to 100 kW of power on target. The uniformity of beam spatial power translates to a one-dimensional heat flux over the irradiated area of the specimen being tested.

Samples tested with lasers are heated with directed radiant energy and experience no external mechanical loading. Specimens may be tested in a variety of environmental conditions (oxidizing, inert, high vacuum), and delicate instrumentation may be used to obtain information that would be overshadowed by loads induced from convective or conductive heating. If flow effects are desired, specimens may also be tested in a wind tunnel with Mach numbers ranging from 0.1 to 2.2. By exploiting the performance of laser operations, materials can be directly compared. This comparison is invaluable when evaluating the performance of a replacement material in an existing design or the performance of several new materials relative to each other.

Analytical modeling can benefit greatly from data gathered from laser material testing. By providing a flat heat flux profile, material response can be assumed to be one dimensional. The amount and variety of performance data that can be obtained and the instrumentation range are extensive. The only restriction for sample instrumentation is to avoid placing it or anything other than the sample in the laser beam path. Examples of historical material response data collected for modeling support include temperature profiles, density profiles, pressure profiles, surface temperature response, and mass loss measurements. Much of the data is measured as a transient variable while the test specimen is heated. Testing and data acquisition are usually driven by the need to correlate the transient response of mathematical material models against high-fidelity test data.

Thermographic Nondestructive Evaluation of the Space Shuttle Main Engine Nozzle

JAMES L. WALKER and Samuel S. Russell

Marshall Space Flight Center/ED32
Huntsville, AL 35812 USA
Phone: 256-961-1784 (Walker); 256-544-4411 (Russell)
Fax: 256-544-9326
E-mail: james.l.walker@msfc.nasa.gov
sam.russell@msfc.nasa.gov

Matthew D. Lansing
University of Alabama in Huntsville
Research Institute
Phone: 256-544-3953
E-mail: matt.lansing@msfc.nasa.gov

Paul Caraccioli
Marshall Space Flight Center/MP32
Huntsville, AL 35812 USA
Phone: 256-544-0064
E-mail: paul.a.caraccioli@msfc.nasa.gov

The nozzles of the Space Shuttle Main Engines (SSMEs) consist of over 1,000 tapered Inconel coolant tubes brazed to a stainless-steel structural jacket. Liquid hydrogen under high pressure flows through the tubing, from the aft to forward end of the nozzle, to maintain a thermal balance between the rocket exhaust and the nozzle wall. Three potential problems occur within the SSME nozzle coolant tubes as a result of manufacturing anomalies and the highly volatile service environment. These problems are (1) poor or incomplete bonding of the tubes to the structural jacket, (2) leaks into the interstices between the tubes and jacket, and (3) leaks into the inner hot wall or flame side of the nozzle. Hot wall leaks can be identified by applying a liquid leak check solution to the inner surface of the nozzle while it is pressurized with helium gas. X-ray techniques are used to identify the condition of the braze line. The identification of interstitial leaks between the tubing and structural jacket is not as well defined and, classically, has been the most problematic. Interstitial leaks are often found by first identifying which tubes are leaking by the application of a liquid leak check solution where the interstitials vent at the aft end of the nozzle. Then, through a trial-and-error approach, tubes are cut open, and an angioplasty device is inserted to block off a specific region of the tube. Pressure is reapplied, and the interstices are rechecked for leaks. Also, a borescope is typically used to look at the inside of suspect tubes. This process is repeated until the source is located or all suspect tubes are tested. If the leak cannot be found and it is severe enough, the nozzle must be pulled from service. Because of manifolding within the nozzle, the identification of which tube is leaking is difficult, leading to the opening and inspection of many tubes that were previously undamaged. Also, when the leak originates from multiple sources, it is difficult to tell if the angioplasty device has isolated a leaking tube.

Methods and results presented address the thermographic identification of interstitial leaks of the SSME nozzles. A highly sensitive digital infrared camera records the cooling effects associated with the leak source. Images of the inner hot wall surface of the nozzle are acquired as the nozzle is pressurized and are then subtracted from a reference image taken before pressurization to further enhance the thermal signature of the leak. The method provides a nonintrusive way to localize the leaking tube and the exact leak source to within a very small axial length. Many of the factors that influence the inspectability of the nozzle are addressed, including pressure rate, peak pressure, gas type, ambient temperature, and surface preparation.

Fluorescent Cleaning Process

JIM DEARDORFF

Superior Coatings, Inc.
1713 Bryan Street, P.O. Box 317
Chillicothe, MO 64601 USA
Phone: 660-646-6355
Fax: 660-646-3691

In recent years, the tremendous growth in available technology, the resulting trend toward component miniaturization, and increased product reliability have challenged many companies to upgrade their current cleaning operations to satisfy the higher quality standards required by new product designs.

A new, integrated process that combines cleaning methods with fluorescence-based monitoring promises to increase operational efficiency significantly and provide low-cost quality assurance to a greater range of cleaning operations. Fluorescent cleaning uses modified cleaning agents containing an internal fluorescent/phosphorescent (FP) dye to produce a highly visible response when exposed to ultraviolet or visible illumination.

FP cleaning offers many performance advantages over traditional cleaning operations. Uniform coverage of all surface areas, including those of small parts or parts with complicated surfaces, and complete saturation of available contaminants can be easily monitored by suitable light inspection. After removal of the FP cleaner and suspended contaminants, cleanliness quality is verified by the total absence of visible fluorescence. Fluorescent inspections can be performed at virtually any point during the assembly phase or at later intervals to support ongoing contamination control maintenance.

Verification of Shearography NDE Methods on Space Shuttle, X-33, and Delta IV Launch Vehicles

JOHN W. NEWMAN

Laser Technology, Inc.
105 S. Germantown Pike
Norristown, PA 19403 USA
Phone: 610-631-5043
Fax: 610-631-0934
E-mail: Jwnewman50@aol.com

Laser shearography nondestructive evaluation (NDE) was first implemented in aerospace production of the U.S.A.F. B-2 program in the 1980s. Since then, it has become widely accepted for the inspection of metal engine components, composites, honeycomb structures, and thermal protection material on launch vehicle systems. Shearography NDE images surface strain caused by the presence of subsurface anomalies when a repetitive load is applied to the structure. Very successful, high-speed inspection techniques have been developed using shearography with acoustic stress to image disbonds under sprayed-on foam insulation (SOFI) applied to aluminum cryogenic fuel tanks. Typically, 6 to 8 square feet of surface area are inspected in less than 1 second.

A large robotic shearography system has been implemented in production for the LO_2 and LH_2 tanks on the Delta IV using this technology. In addition, shearography methods were validated and implemented on the X-33 XRS-2200 aerospike rocket engine thrust ramps. Both the cooling channels and the metal honeycomb support structure were inspected. This provided rapid engineering for production engineering refinement of processes and on-site NDE in near-real time, which reduced costs and allowed inspection of braze bonds that otherwise would not have been able to be inspected.

This paper will discuss the technology and quality and cost benefits of shearography NDE as applied to rapid launch vehicle NDE and health monitoring. It will also provide specific examples of NDE verification on three programs.

Thermographic Analysis of Composite Cobonds on the X-33

JAMES L. WALKER

Marshall Space Flight Center/ED32
Huntsville, AL 35812 USA
Phone: 256-961-1784
Fax: 256-544-9326
E-mail: james.l.walker@msfc.nasa.gov

Matthew D. Lansing
University of Alabama in Huntsville
Research Institute
Huntsville, AL 35899 USA
Phone: 256-544-3953
E-mail: matt.lansing@msfc.nasa.gov

Samuel S. Russell
Marshall Space Flight Center/ED32
Huntsville, AL 35812 USA
Phone: 256-544-4411
Fax: 256-544-9326
E-mail: sam.russell@msfc.nasa.gov

During the manufacture of the X-33 liquid hydrogen (LH_2) Tank 2, a total of 36 reinforcing caps were inspected thermographically. The pre-cured reinforcing sheets of graphite epoxy were bonded to the tank using a wet cobond process with vacuum bagging and low-temperature curing. Manufacturing difficulties caused by a combination of the size of the reinforcing caps and their complex geometry led to a potential for trapping air in the bondline. An inspection process was needed to ensure that the bondline was free of voids before it had cured so that measures could be taken to massage out the entrapped air or to remove the cap and perform additional surface matching.

Infrared thermography was used to perform this inspection and to document the final cured condition of the caps. The thermal map of the bondline was acquired by heating the cap with either a flash lamp or a set of high-intensity quartz lamps and then viewing it during cool down. The inspections were performed through the vacuum bag, and voids were characterized by localized hot spots. To ensure that the cap had bonded properly to the tank, a post “flash” thermographic investigation was performed. Regions that had opened after the preliminary inspection were marked and filled by drilling small holes in the cap and injecting resin. This process was repeated until all critical-size voids were filled.

Evaluation of Forces on the Welding Probe of the Automated Retractable Pin-Tool (RPT)

R. JEFFREY DING

Marshall Space Flight Center/ED33
Huntsville, AL 35812 USA
Phone: 256-544-2700
Fax: 256-544-1660
E-mail: jeff.ding@msfc.nasa.gov

The NASA invention entitled "The Hydraulic Controlled Auto-Adjustable Pin Tool for Friction Stir Welding" (U.S. Patent 5,893,507), better known as the Retractable Pin-Tool (RPT), has been instrumented with a load-detecting device allowing the forces placed on the welding probe to be measured. As the welding probe is plunged into the material, the forces placed on the probe can now be characterized. Of particular interest are those forces experienced as the welding probe comes within close proximity to the back-up anvil. For a given material, it is believed that unique forces are generated relative to the distance between the welding probe and the anvil. The forces have been measured and characterized for several materials, and correlations have been made between these forces and the pin's position relative to the backside of the weld material.

Friction Stir Weld Modeling at MSFC: Kinematics

ARTHUR C. NUNES, JR.

Marshall Space Flight Center/ ED33
Huntsville, AL 35812 USA
Phone: 256-544-2699
Fax: 256-544-0212
E-mail: Arthur.Nunes@msfc.nasa.gov

A "merry-go-round" computation model makes it easier to visualize how tracer experiments of varied sorts (chemical, shot, wire) are consistent with a "moving plug model" of flow around the friction stir welding pin-tool. The moving plug model comprises a two-fold flow: (1) a primary rotation of a plug of metal with the tool, which moves metal around the tool by wiping it on and off the plug, and (2) a secondary, relatively slow circulation induced by the threads on the tool resembling a circular vortex ring around the tool.

Spinforming Development Trials of Friction Stir Welded Al 2195

DAVID KINCHEN

Lockheed Martin Space Systems, Michoud Operations
Department 4310 Bldg. 350/1st/C5
P.O. Box 29305
New Orleans, LA 70189 USA
Phone: 504-257-1454
Fax: 504-257-1210
E-mail: david.kinchen@maf.nasa.gov

Spinforming is a hot forming process used to produce near-net-shape hardware, such as domes for aerospace applications. The process is applicable for a variety of alloys, from stainless-steel to aluminum. Spinforming of domes for cryogenic tankage is currently limited to approximately 16 feet in diameter because of the size of available starting stock; thus, spinforming of large domes, such as that for the External Tank, while cost effective, has been unattainable.

Friction stir welding is a solid-state process in which material is heated and plasticized, forming a fine-grained weldment between the parts being welded. The improved quality, strength, and ductility of friction stir welds in aluminum provide the ability to produce unlimited size starting stock for the spinforming process, thus affording the possibility of spinforming domes significantly larger than possible with the current process.

This paper presents the results of development spinform trials for three 0.20-in. thick friction stir welded Al 2195 domes. Material heat treatment and spinforming process steps are presented, along with lessons learned and process changes made during the trials. The results of nondestructive evaluation, dome dimensions, tensile strength, yield strength, and elongation are presented. Also included are data from preliminary evaluations that simulated post friction stir weld heat treatment and stretching and aging processes.

Aluminum Lithium Alloy 2195 Fusion Welding Improvements with New Filler Wire

GERRY BJORKMAN

Lockheed Martin Michoud Space Systems, Huntsville Technical Operations
Marshall Space Flight Center, Bldg. 4711
Huntsville, AL 35812 USA
Phone: 256-961-4438
Fax: 256-544-5786
E-mail: Gerry.Bjorkman@msfc.nasa.gov

Carolyn Russell
Marshall Space Flight Center/ED33
Huntsville, AL 35812 USA
Phone: 256-544-2705
Fax: 256-544-0212
E-mail: Carolyn.K.Russell@msfc.nasa.gov

NASA Marshall Space Flight Center, Lockheed Martin Michoud Space Systems, and McCook Metals have developed an aluminum-copper weld filler wire for fusion welding 2195 aluminum lithium. The aluminum-copper based weld filler wire, identified as B218, is the result of 6 years of weld filler wire development funded by NASA, Lockheed Martin, and McCook Metals. The Super Lightweight External Tank for the Space Shuttle Program consists of 2195 welded with 4043 aluminum-silicon weld filler wire. The B218 filler wire chemistry was developed to produce enhanced 2195 weld and repair weld mechanical properties. An initial characterization of the B218 weld filler wire was performed and consisted of initial weld and repair weld evaluation comparing B218 and 4043. The testing involved room-temperature and cryogenic tensile testing and fracture toughness testing. B218 weld filler wire produced enhanced initial weld and repair weld tensile and fracture properties over 4043. B218 weld filler wire proved to be superior to 4043 weld filler wire for welding 2195 and other aluminum lithium alloys.

Dissimilar Metal Joining

CAROLYN RUSSELL

Marshall Space Flight Center/ED33
Huntsville, AL 35812 USA
Phone: 256-544-2705
Fax: 256-544-0212
E-mail: Carolyn.K.Russell@msfc.nasa.gov

Graeme Aston
Electric Propulsion Laboratory, Inc.
Monument, CO 80903 USA

Electrodeless Plasma Welding was developed through the NASA Small Business Innovative Research (SBIR) program as a space welding tool by Electric Propulsion Laboratory, Inc. The process is a new way of welding, in that it uses a unique vacuum-transferred plasma arc as the energy source for melting the metal to be joined. Under a subsequent SBIR Phase I contract, the proof of concept for the welding of dissimilar metal joints using this process was demonstrated successfully. This presentation will discuss the Electrodeless Plasma Welding process and the microstructures of dissimilar metallic joints and will propose a concept for joining metals to ceramics.

Fabrication of Composite Combustion Chamber/Nozzle for Fastrac Engine

T. LAWRENCE, M. Prince, and S. Tillery

Marshall Space Flight Center/ED34
Huntsville, AL 35812 USA
Phone: 256-544-2660 (Lawrence)
256-544-2678 (Prince)
256-544-8651 (Tillery)
Fax: 256-544-5877
E-mail: Timothy.W.Lawrence@msfc.nasa.gov
Mike.Prince@msfc.nasa.gov
Scott.W.Tillery@msfc.nasa.gov

R. Beshears and M. Suits
Marshall Space Flight Center/ED32
Huntsville, AL 35812 USA
Phone: 256-544-2550 (Besheas)
256-544-8336 (Suits)
Fax: 256-544-6869
E-mail: Ronald.D.Besheas@msfc.nasa.gov
Michael.W.Suits@msfc.nasa.gov

S. Burlingame
Marshall Space Flight Center/ED33
Huntsville, AL 35812 USA
Phone: 256-544-8860
Fax: 256-544-7255
E-mail: Steven.W.Burlingame@msfc.nasa.gov

W. Peters
Marshall Space Flight Center/TD61
Huntsville, AL 35812 USA
Phone: 256-544-5399
Fax: 256-544-2032
E-mail: Warren.Peters@msfc.nasa.gov

L. Burns, M. Kovach, and K. Roberts
Thiokol Propulsion Group
Marshall Space Flight Center, Building 4712
Huntsville, AL 35812 USA
Phone: 256-544-0991

The Fastrac engine, developed by Marshall Space Flight Center for the X-34 vehicle, began as a low-cost engine development program for a small booster system. One of the key components to reducing the engine cost was the development of an inexpensive combustion chamber/nozzle. Fabrication of a regeneratively cooled thrust chamber and nozzle was considered too expensive and time consuming. In looking for an alternate design concept, the Space Shuttle's Reusable Solid Rocket Motor Project provided extensive background with ablative composite materials in a combustion environment. An integral combustion chamber/nozzle was designed and fabricated with a silica phenolic ablative liner and a carbon-epoxy structural overwrap. This paper describes the fabrication process and developmental hurdles that were overcome for the Fastrac engine one-piece composite combustion chamber/nozzle.

Large Composite Structures Processing Technologies For Reusable Launch Vehicles

R. G. CLINTON, JR.

Marshall Space Flight Center/ED34
Huntsville, AL 35812 USA
Phone: 256-544-2682
Fax: 256-544-2825
E-mail: Corky.Clinton@msfc.nasa.gov

John H. Vickers
Marshall Space Flight Center/ED34
Huntsville, AL 35812 USA
Phone: 256-544-3581
Fax: 256-544-7255
E-mail: John.H.Vickers@msfc.nasa.gov

Norman J. Johnston
Langley Research Center
Hampton, VA 23681-2199 USA
Phone: 757-864-4260
Fax: 757-864-8312
E-mail: N.J.Johnston@larc.nasa.gov

William M. McMahon, *et al.*
Marshall Space Flight Center/ ED34
Huntsville, AL 35812 USA
Phone: 256-544-2802
Fax: 256-544-7255
E-mail: William.M.Mcmahon@msfc.nasa.gov

Polymer matrix composite (PMC) materials historically have offered the benefits of tailorable properties and high specific strength and stiffness. These characteristics translate into substantial benefits to Reusable Launch Vehicles (RLVs) through the application of these materials to weight-critical components and structures. PMCs also offer attractive economies of scale and automated fabrication methodologies. To realize the benefits of these materials, however, technology challenges in the processing and manufacturing disciplines must be addressed. Production of recent large-scale composite cryotanks has involved composite component construction utilizing fiber placement equipment and autoclave curing. Utilizing the same processing approach for the large structures envisioned for RLVs would require development and fabrication of such equipment at unprecedented scales. Alternatives to autoclave processing are being developed by NASA and industry; however, they have yet to be matured. These include (a) thermoplastic forming, such as heated head robotic tape placement and other supporting processes; (b) electron beam curing, both bulk and ply-by-ply automated placement; and (c) Resin Transfer Molding and Vacuum-Assisted Resin Transfer Molding. Development activities on such out-of-autoclave processes, particularly those involving automated placement techniques, will be presented.

Composite, Cryogenic, Conformal, Common Bulkhead, Aerogel-Insulated Tank (CBAT) Materials and Processing Methodologies

MICHAEL P. KOVACH and J. Keith Roberts

Thiokol Propulsion
SEHO Operations
P.O. Box 707, M/S 200
Brigham City, UT 84302 USA
E-mail: kovacmp@thiokol.com

William M. McMahon
Marshall Space Flight Center/ED34
Huntsville, AL 35812 USA
Phone: 256-544-2802
Fax: 256-544-7255
E-mail: William.M.Mcmahon@msfc.nasa.gov

Jeffrey L. Finckenor
Marshall Space Flight Center/ED23
Huntsville, AL 35812 USA
Phone: 256-544-7041
Fax: 256-544-8528
E-mail: Jeffrey.L.Finckenor@msfc.nasa.gov

The objective of the Composite, Cryogenic, Conformal, Common Bulkhead, Aerogel-insulated Tank (CBAT) Program is to evaluate the potential for using various new technologies in next-generation Reusable Launch Vehicles (RLVs) through design, fabrication, and testing of a subscale system. The new technologies include polymer matrix composites (PMCs), conformal propellant storage, common bulkhead packaging, and aerogel insulation. NASA and Thiokol Propulsion from Cordant Technologies are working together to develop a design and the processing methodologies that will allow integration of these technologies into a single structural component assembly. Such integration will significantly decrease subsystem weight and reduce shape, volume, and placement restrictions, thereby enhancing overall launch system performance.

This paper/presentation focuses on the challenges related to materials and processes that were encountered and overcome during this program to date.

Coating Removal Technology Using Starch-Based Abrasives: A Review of Current Aerospace Depaint Applications using the EnviroStrip® Dry Stripping Process

DENIS MONETTE

ADM/Ogilvie
995 Mill St.
Montreal, Quebec, Canada, H3C1Y5
Phone: 514-846-8516
Fax: 514-937-9578
E-mail: envirostriptc@sprint.ca

Cameron Drake
ADM/Ogilvie
302 Island Drive
Melbourne Beach, FL 32951 USA
Phone: 321-728-9100
Fax: 321-728-0175
E-mail: cdrake@mindspring.com

Because of stringent new environmental regulations enacted in the past 10 years, one of the largest challenges for aerospace materials and process engineers has been to find environmentally acceptable replacements for methylene chloride- (MC-) based chemical paint strippers. The chemical was found to be very effective in removing tough polyurethane/epoxy coating systems typically found on aircraft fuselages. Because MC evaporates quickly [very high in volatile organic compounds (VOCs)], it reduced the potential for over dwelling and ingress problems on or in sensitive aircraft structures. The main reason that MC is being phased out is that it is damaging to the environment and is a very toxic chemical, damaging the health of workers exposed to it.

A myriad of new environmentally acceptable (EA) chemicals has been developed and tested in the last 5 years to replace MC. The EA chemicals are considered safer for the planet and workers because the chemicals are stable and have very low evaporation rates. Some strongly believe, however, that the new EA chemicals may still pose health risks to workers and may be damaging to structures because of long-term ingress problems.

Ten years ago, a new dry media paint removal process was introduced to the aerospace industry. This new media, called EnviroStrip®, was considerably more gentle than other dry media used at the time, *i.e.*, plastic media. EnviroStrip® is made from a biodegradable renewable resource: wheat starch. Extensively tested, approved, and used in production applications by Northrop Grumman, Raytheon, Cessna, and Boeing, the EnviroStrip® process is being embraced for its coating removal effectiveness on metals and composite substrates. In 1998, a new type of EnviroStrip® media (XL), made from a corn hybrid polymer, was introduced and is also now being successfully used by major companies in the aerospace industry.

This paper will describe the methods to manufacture the media, the equipment to apply the process, and the various applications for this technology in the aerospace industry. We will review the production use of this dry stripping method on the B-2 bomber, the Space Shuttle, and other aircraft types. Special applications such as selective stripping, metal bond adhesive removal, and interior aircraft panel refurbishment will also be reviewed.

Removal of Zirconia Thermal Barrier Coatings and MCrAlY Bond Coatings from Turbine Blades: A Comparison of Methods Based on Chemical Stripping, Water Jet, and Salt Bath

A. SCRIVANI

Firenze University
Chemistry Department
Via Cavour 82
Firenze, Italy
Phone: 39-055-2757794

University of Parma
Department of Industrial Engineering
Viale delle Scienze
Parma, Italy
Phone: 39-0525-406217
Fax: 39-0525-401612
E-mail: andreascrivani@turbocoating.it

U. Bardi, G. Ballerini, and D. Bonacchi
Firenze University
Chemistry Department
Via Cavour 82
Firenze, Italy
Phone: 39-055-2757794

M. Fantini
Galvanica Parmense
Via Romagnoli 3
S. Polo di Torrile
Parma, Italy
Phone: 39-055-2757794

R. Groppetti and S. Ianelli
University of Parma
Department of Industrial Engineering
Viale delle Scienze
Parma, Italy

G. Rizzi
Turbocoating S.p.A.
Via Volta 3
Rubbiano
Parma, Italy

In the aerospace field, as well as in the stationary gas turbine field, thermal spray coatings are getting more and more important in the improvement of nickel superalloys materials surface properties. Thermal spray coatings are commonly used as antioxidation materials (mainly MCrAlY alloys) and as thermal barrier coatings (mainly yttria partially stabilized Zirconia) and are applied on nickel superalloys, *e.g.,* different kinds of Inconel.

An important aspect in the production of these coatings is the methodologies used for coatings removal. This paper concerns the characterization of surfaces before and after removal of both Zirconia and MCrAlY thermal spray coatings. Different technologies are studied, *i.e.,* chemical stripping by hydrochloric acid, water jet stripping, and salt bath stripping. Surface properties are investigated by 3-D profilometer, scanning electron microscopy, and Auger spectroscopy. Surface properties of new components just after casting before coating and after stripping are compared. Mechanical properties of stripped components are investigated by submitting recoated components to thermal shock test. Furthermore, control procedures of stripping are considered.

Economic comparison has been carried out among the three considered technologies. The results show that chemical stripping is particularly suitable for MCrAlY coating removal and does not affect the base material. Water jet stripping can successfully be used for Zirconia-MCrAlY system removal; attention shall be paid to base material damages. On the other hand, salt bath technologies can be used for thermal barrier coatings removal.

Joint EPA/NASA/USAF Interagency Depainting Study

MARCEIA CLARK-INGRAM

Marshall Space Flight Center/ED36
Huntsville, AL 35812 USA
Phone: 256-544-6229
Fax: 256-544-5478
E-mail: Marceia.A.Clark.Ingram@msfc.nasa.gov

Environmental regulations such as National Emission Standards for Hazardous Air Pollutants (NESHAPs) are drivers for the implementation of environmentally compliant methodologies in the manufacture of aerospace hardware. In 1995, the Environmental Protection Agency (EPA) promulgated the NESHAP for the Aerospace Manufacture and Rework Facilities (Aerospace NESHAP). Affected facilities were to be in compliance by September 1998.

Several aerospace manufacturing operations are regulated within the Aerospace NESHAP, including depainting operations. Methylene chloride is the chemical stripper historically used in coating removal applications. The amount of methylene chloride that can be used for such applications is strictly regulated within the Aerospace NESHAP. The allowable usage is 26 gallons/year for a commercial aircraft and 50 gallons/year for a military craft.

NASA, the EPA, and the United States Air Force combined resources to evaluate the performance of seven alternative depainting processes: chemical stripping (non-methylene chloride), carbon dioxide blasting, xenon flashlamp, carbon dioxide laser stripping, plastic media blasting, sodium bicarbonate wet stripping, waterjet blasting and wheat starch blasting. An epoxy primer and polyurethane topcoat system was applied to 2024-T3 clad and non-clad aluminum test specimens. Approximately 200 test specimens were evaluated in this study. Each coupon was subjected to three, four, or five complete depainting cycles.

This paper discusses the conclusions from the study, including the test protocol, test parameters, and achievable strip rates for the alternative depainting processes. Test data include immersion corrosion testing, sandwich corrosion testing, and hydrogen embrittlement testing for the non-methylene chloride chemical strippers. Additionally, the cumulative effect of the alternative depainting processes on the metallurgical integrity of the test substrate is addressed with the results from tensile and fatigue evaluations.

Evaluation of Various Depainting Processes on Mechanical Properties of 2024-T3 Aluminum Substrate

PRESTON B. MCGILL

Marshall Space Flight Center/ED33
Huntsville, AL 35812 USA
Phone: 256-544-2604
Fax: 256-544-5877
E-mail: Preston.B.McGill.Dr@msfc.nasa.gov

This paper reports the results of a test program to evaluate the effects of various depainting processes on the mechanical performance of the substrate material. Tensile, fatigue, and crack detectability tests were performed on 2024-T3 aluminum substrate subjected to plastic media blast, wheat starch blast, water jet blast, and flashlamp depainting processes. Tests were performed in accordance with ISO/SAE MA 4782 guidelines. Data from baseline (non-processed) test panels are compared to data from processed panel specimens subjected to simulated aging cycles. Although the number of tests performed in each series of tests is small, a statistical analysis of data is presented, which compares mean fatigue life and crack length detectability to baseline values. The raw data are also presented for review.

Low-Cost Ceramic Matrix Composites

WITOLD KOWBEL, C. Bruce, K.T. Tsou, and J.C. Withers

MER Corporation
7960 S Kolb Road
Tucson, AZ 85706 USA
Phone: 520-574-1980 x22
Fax: 520-574-1983
E-mail: kowbel@mercorp.com

Ceramic matrix composites offer clear advantages over metallic components at high operating temperatures. Several factors hinder their wide application. These include lack of high-temperature stable ceramic fibers, high manufacturing cost, and high machining cost. A new process based upon chemical vapor reaction was developed. It enables near-net-shape, low-cost fabrication of SiC/SiC, C/SiC and C/HfC composites. The processing-structure-property relationship for this new class of composites will be discussed. In addition, propulsion and thermal protection applications at temperatures up to 5,000 °F will be discussed.

Advanced Ceramic Matrix Composites for Aerospace Applications

JOHN GARNIER, Bill Patterson, Bob Klacka, Paul Gray, and Stan Hemstad

Honeywell Advanced Composites, Inc.
400 Bellevue Road
Newark, DE 19713 USA
Phone: 302-631-1323
Fax: 302-631-1320
E-mail: john.garnier@honeywell.com

Advanced ceramic matrix composites (CMCs) are an enabling technology for hypersonic trans-aerospace missile and turbine engine applications demanding high performance. Honeywell Advanced Composites has developed a palette of CMCs in limited commercial production and in various stages of evaluation for aerospace-related programs. CMCs include carbon fiber-reinforced silicon carbide (C/SiC) and enhanced silicon carbide fiber-reinforced silicon carbide (E-SiC/SiC). Hardware fabrication can use chemical vapor infiltration (CVI), silicon melt infiltration (MI), and chemical conversion processing techniques. C/SiC is a leading thermal heat shield protection material for several heat shield structural designs and has demonstrated excellent low-erosion hypersonic leading-edge performance. C/SiC thrusters were successfully flight tested in various missile tests. Because of the material's attributes of low density, high strength, and very high-temperature capability, C/SiC has been in development for linear aero-spike engine applications, including the ramp and pump. SiCf/SiC MI CMC is qualified as the only 2,200-°F, 20-Ksi, long-duration material for NASA's high-speed civil transport advanced turbine engines. Commercial accomplishments also include 15,000 hours of field time in stationary power turbine engines. In development are 2,400-°F SiC/SiC materials and advanced very low system weight SiC/SiC structural mirrors. Recent, open-literature thermal and mechanical data on C/SiC, E-SiC/SiC, and SiC/SiC MI CMC will be presented, including customer-approved hardware and test results.

Rapid Fabrication of Monolithic Ceramic Parts Reinforced with Fibrous Monoliths for Aerospace Applications

R. VAIDYANATHAN, J. Walish, J.L. Lombardi, D. Dent, M. Rigali, and M. Sutaria

Advanced Ceramics Research, Inc.
3292 E. Hemisphere Loop
Tucson, AZ 85706 USA
Phone: 520-434-6392
Fax: 520-573-2057
E-mail: r.vaidyanathan@acrtucson.com

High-temperature, structural ceramics are finding increasing applications as components in gas turbine engines and rocket motors, where significantly greater strength and thermal stability at elevated temperatures are needed. One of the challenges for producing viable air turbo rockets (ATRs) is the manufacture of small, complex, reliable, lightweight, and powerful engines. Ceramic composite materials could be utilized for the compressor, turbine, and nozzle stages, providing excellent mechanical properties at elevated temperatures. Also, the appropriate use of silicon nitride components would reduce the weight of the engine by as much as 30%. The introduction of new materials in engine applications, however, is frequently prohibited by factors such as tooling costs. Development and adoption of Solid Freeform Fabrication (SFF) processes have helped reduce the cost of complex tooling and shortened the development cycle. Advanced Ceramics Research, Inc., (ACR) has developed two unique SFF techniques [Shape Deposition Manufacturing (SDM) and Extrusion Freeform Fabrication (EFF)] for the rapid fabrication of monolithic ceramics and composite components. SDM combines the benefits of additive material processing and the dimensional accuracy of CNC cutting, milling, and drilling operations.

Low fracture toughness limits the use of engineering ceramics in highly loaded structural applications. ACR has developed a new class of low-cost, bi- and multicomponent structural ceramic material (Fibrous Monolith) that exhibits mechanical properties similar to fiber composites. Fibrous Monolithic material has a distinct fibrous texture, consisting of intertwined cells of a primary phase separated by cell boundaries of a tailored secondary phase; shows very high fracture energies, damage tolerance, and graceful failure; and can be manufactured by conventional powder processing techniques using inexpensive raw materials. Typically, the cell is a structural ceramic, and the cell boundary is either a ductile metal or a weakly bonded low-shear strength material. ACR demonstrated the capability of the EFF process for the fabrication of Fibrous Monolith components.

Fracture toughness improvement, however, is achieved at the expense of strength, reducing opportunities for these ceramic composite materials in space applications. To address this problem, ACR evaluated the combination of SDM and EFF for rapid fabrication of monolithic ceramic components reinforced with Fibrous Monolith fibers. The paper will detail the combination of the technologies to create low-cost ceramic fiber-reinforced composites for high-temperature uses. Combining the two technologies will yield a novel rapid prototype manufacturing process to develop ceramic fiber composites. Since EFF and SDM are freeform fabrication techniques, the proposed technique potentially can yield geometrically complex, functional ceramic components directly from CAD designs. Results of mechanical properties and microstructural characterization and samples of complex shapes and parts will be presented.

Concept for Determining the Life of Ceramic Matrix Composites Using Nondestructive Characterization Techniques

MICHAEL EFFINGER

Marshall Space Flight Center/ED34
Huntsville, AL 35812 USA
Phone: 256-544-5637
Fax: 256-544-5877
E-mail: Michael.R.Effinger@msfc.nasa.gov

Bill Ellingson and Todd Spohnholtz
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439 USA
Phone: 630-252-5068 (Ellingson)
630-252-5091 (Spohnholtz)
Fax: 630-252-4798
E-mail: ellingson@anl.gov
spohnholtz@anl.gov

John Koenig
Southern Research Institute
2000 Ninth Avenue South
P.O. Box 55305
Birmingham, AL 35255-5305 USA
Phone: 205-581-2436
E-mail: koenig@sri.org

Damping measurements have been taken on ceramic matrix composite (CMC) turbopump blisks in the as-fabricated, post-proof testing, and post-turbopump testing conditions. These results indicate that damping is able to quantify fatigue of the CMC blisk, giving hope for the potential of determining the actual and residual life of CMC materials using a combination of nondestructive techniques. If successful, this new paradigm for life prediction of CMCs could revolutionize the approach for designing and servicing CMC components, thereby significantly reducing costs for design, development, health monitoring, and maintenance of CMC components and systems. The Nondestructive Characterization (NDC) life prediction approach would complement life prediction using micromechanics and continuum finite element models. This paper reports on the initial concept of NDC life prediction and how changes in damping and ultrasonic elastic modulus data have established the concept as a possibility.

Solid Freeform Fabrication of Continuous Fiber Reinforced Composites for Propulsion Applications

R. VAIDYANATHAN, J. Walish, M. Fox, M. Rigali and M. Sutaria

Advanced Ceramics Research, Inc.
3292 E. Hemisphere Loop
Tucson, AZ 85706 USA
Phone: 520-434-6392
Fax: 520-573-2057
E-mail: r.vaidyanathan@acrtucson.com

John W. Gillespie, Jr., and Shridhar Yarlagadda
University of Delaware
Center for Composite Materials
Newark, DE 19716-3144 USA
Phone: 302-831-8702 (Gillespie)
302-831-4941 (Yarlagadda)
Fax: 302-831-8525
E-mail: gillespie@ccm.udel.edu
yarlagadda@ccm.udel.edu

Michael Effinger
Marshall Space Flight Center/ED34
Huntsville, AL 35812 USA
Phone: 256-544-5637
Fax: 256-544-5877
E-mail: Michael.R.Effinger@msfc.nasa.gov

Materials for propulsion-related applications must demonstrate excellent ablation and oxidation resistance at temperatures approaching 3,500 ∞C, adequate load-bearing capabilities, non-catastrophic failure modes, and the ability to withstand transient thermal shock. Propulsion material property requirements include low density, high elastic modulus, low thermal expansion coefficient, high thermal conductivity, excellent erosion and oxidation/corrosion resistance, and flaw insensitivity. Often, they must be able to be joined and survive thermal cycling and multi-axial stress states; for reusable applications, they must retain these attributes after prolonged exposure to extremely harsh chemical environments. Finally and possibly most importantly, these materials need to be of lower cost and readily available in large quantities.

Advanced Ceramics Research, Inc., (ACR) has developed a low-cost, flexible manufacturing process for Zr and Hf-based carbon fiber-reinforced composites. The Continuous Composite Co-extrusion (C^3) process is a variation of ACR's Fibrous Monolith manufacturing process for low-cost structural ceramic materials with carbon fiber reinforcements. C^3 incorporates carbon fibers to fabricate *in-situ* carbide and boride-matrix/carbon fiber composites. ACR is developing a Solid Freeform Fabrication (SFF) approach to produce Hf- and Zr-based ceramic composite components reinforced with continuous carbon fiber tows. The process is simple, robust, and applicable to a range of material systems. The technique was originally developed at the University of Delaware Center for Composite Materials for rapid fabrication of polymer matrix composites; the technique was called automated tow placement (ATP).

The paper will detail the SFF process. The results of mechanical properties and microstructural characterization will be presented, with examples of complex shapes and parts. We believe the process will create complex shaped parts for propulsion applications at an order of magnitude lower cost than CVI and PIP processes.

An Example of Economic Value in Rapid Prototyping

JOHN R. REAGAN

Glenn Research Center, MS 50 – 4
21000 Brookpark Road
Cleveland, OH 44135 USA
Phone: 216-433-2357
Fax: 216-433-5270
E-mail: John.R.Reagan@lerc.nasa.gov

Edward P. Braunscheidel
Glenn Research Center, MS 5 – 10
21000 Brookpark Road
Cleveland, OH 44135 USA
Phone: 216-433-6298
Fax: 216-433-8000
E-mail: Edward.P.Braunscheidel@lerc.nasa.gov

Herbert A. Lawrence, Jr.
Glenn Research Center, MS 50 – 2
21000 Brookpark Road
Cleveland, OH 44135 USA
Phone: 216-433-3363
E-mail: Herbert.A.Lawrence@lerc.nasa.gov

Robert L. Hauer
Glenn Research Center, MS 50 – 1
21000 Brookpark Road
Cleveland, OH 44135 USA
Phone: 216-433-2216
E-mail: Robert.L.Hauer@lerc.nasa.gov

The Sinterstation 2500 Plus at Glenn Research Center (GRC) has made major contributions to research and development in manufacturing engineering. Continuous development of new types of materials and versatile uses of current materials allow the Selective Laser Sinterstation to support the entire product development process. Specific application segments include functional modeling, prototype manufacturing, investment casting, injection molding, and direct manufacturing. The Rapid Prototyping area has committed this technology to aid in the advancement of projects such as Hybrid Hyperspeed Propulsion, Turbomachinery and Combustion Technology, and the Active Noise Control Facility.

GRC's Rapid Prototyping Facility is committed to development of cutting-edge manufacturing technology. This paper focuses on a single project from our Turbomachinery and Propulsion Systems Division, Compressor Branch, where a concept for highly twisted fan blades presented a visualization problem that was rapidly solved at low cost through model manufacturing in Duraform material. A full-scale model prototype saved hours of interpreting plots and CAD model pictures in attempts to fully understand hardware configuration. Cost savings were in the neighborhood of $25,000, and a delivery time of days rather than months (by conventional manufacturing technology) was achieved. Designers and engineers saw their concepts in actual form long before conventional manufacturing technology would allow. In 4 days, the rapid prototyping process produced the exact blade shapes, which were then used for discussion, resulting in design revisions for structural and manufacturing reasons.

In the future, the rapid prototyping processes, in conjunction with our materials division, will allow the direct production of alloy powdered metals parts.

High-Efficiency Monolithic Lightweight Aluminum Cast Structure

JOHN BOWKETT

Nu-Cast, Inc.
29 Grenier Field Road
Londonderry, NH 03053 USA
Phone: 603-432-1600
Fax: 603-432-0724
E-mail: nci@grolen.com

Nu-Cast, Inc., is manufacturing highly efficient, low-cost truss-like platforms/structures using the investment casting process developed at Nu-Cast, Inc., and the current rapid prototyping capabilities of steriolithography (SLA). This integrated production process allows for direct transfer of the computer design into hardware with a minimum of compromising fabrication restrictions. In the monolithic 3D-truss approach, control of structural integrity and thermal homogeneity is significantly improved over conventional multipart assemblies because of the elimination of most joint problems and their analytical uncertainties. For example, preliminary analysis of a typical 3D-truss-based instrument platform indicates a potential increase in stiffness up to 130X when compared to a plate of equal mass and area. Localized high-stress areas can be eliminated easily using this approach; additional material can be added locally during normal detailed design to satisfy the part's system requirement and to allow an efficient structural design to become a reality. Additionally, there can be a significant cost reduction for this monolith, compared to multipart assemblies, especially where tight tolerances are not system-functional but are only required for individual piece-part assembly/interface. The improved component performance achievable at a given weight with reduced resource expenditure will clearly support the NASA mandate to "do more with less."

Preliminary Component Integration Utilizing Rapid Prototyping Techniques

KEN COOPER

Marshall Space Flight Center/ED34
Huntsville, AL 35812 USA
Phone: 256-544-8591
Fax: 256-544-8970
E-mail: Ken.Cooper@msfc.nasa.gov

Pat Salvail
IITRI
Marshall Space Flight Center/Bldg. 4612
Huntsville, AL 35812 USA
Phone: 256-544-1818
Fax: 256-544-5512
E-mail: Pat.Salvail@msfc.nasa.gov

One of the most costly errors committed during the development of any element to be used in the space industry is the lack of communication between design and manufacturing engineers. One of the most important tools that should be utilized in the development stages by both design and manufacturing disciplines is rapid prototyping. Communication levels are intensified with the injection of functional models that are generated from a drawing. At Marshall Space Flight Center, we have begun to use this discipline regularly as a process by which hardware may be tested for design and material compatibility.

During the initial stages of the Shooting Star Experiment, for example, rapidly produced absorbers were cast of a superalloy to be used in thermal experiments, before the procurement of the rhenium hardware. In another instance, during the design and development of the Simplex Pump, various articles were cast in an effort to verify castability of the candidate materials. The design team was able to plan ahead and allow for machining and other fabrication costs because of the data gained from continuous auditing made possible by rapid prototyping. These examples have shown how the use of rapid prototyping, when used in the early stages of development, can save both time and money.

We will show other scenarios in which these tools have and will continue to be cost effective. Be it quality-enhancing casting design verification, a pattern substitute for a short production run, or simply a show-and-tell piece for the lead engineer, rapid prototyping and its use in the early stages of manufacture is the avenue of the future.

Multifunctional Carbon Foams for Aerospace Applications

DARREN K. ROGERS and Janusz Plucinski

Touchstone Research Laboratory, Ltd.
Triadelphia, WV 26059 USA
Phone: 304-547-5800
Fax: 304-547-5764
E-mail: dkr@gold.trl.com

Carbon foams produced by the controlled thermal decomposition of inexpensive coal extracts exhibit a combination of structural and thermal properties that make them attractive for aerospace applications. Their thermal conductivity can be tailored between 0.5 and 100 W/mK through precursor selection/modification and heat treatment conditions; thus, they can serve in either thermal protection or heat transfer systems such as heat exchangers. Because their structure is essentially a 3D random network of graphite-like members, they also can be considered low-cost, easily fabricated replacements for multi-directional structural carbon fiber preforms. Strengths of over 4000 psi in compression are common. Their density can be designed between 0.1 and 0.8 g/cm^3, and they can be impregnated with a variety of matrices or used, unfilled, in sandwich structures. These foams also exhibit intriguing electrochemical properties that offer potential in high-efficiency fuel cell and battery applications, mandrels and tooling for composite manufacture, ablative performance, and fire resistance.

This paper presents the results of research conducted under NASA SBIR Topic 99.04.01, General Aviation Technology, supported from Langley Research Center. The potential of foam design through precursor selection, cell size and density control, density grading, and heat treatment is demonstrated.

LOX Compatibility of Composite Materials

TIM VAUGHN

Marshall Space Flight Center/ED35
Huntsville, AL 35812 USA
Phone: 256-544-2607
Fax: 256-544-5786
E-mail: Timothy.P.Vaughn@msfc.nasa.gov

The development of reusable launch vehicle systems for a single-stage-to-orbit vehicle requires that a vehicle, at liftoff, have 85% to 94% of its mass consist exclusively of propellants. These dry mass requirements drive designs to utilize stronger, lighter weight materials for structures. This technology development focus has allowed the introduction of composite materials in lieu of conventional metallic materials because of their higher specific strengths. Composite materials were used successfully for the liquid hydrogen tanks for the DC-XA, and a multi-lobed liquid hydrogen tank will be used for the X-33.

Another potential non-traditional application for composite materials is liquid oxygen tanks; this application is still being investigated. Traditionally, organic materials have been avoided wherever possible, because of the potential fire hazard and the fact that composites fail conventional oxygen compatibility requirements. The potential weight savings, however, warrant investigation of the use of polymeric composite materials in oxygen environments. Since composites fail the conventional, time-proven test methods because they are considered flammable by test, we have embarked on an innovative approach to oxygen compatibility testing and evaluation focused on the use environments and attempts to eliminate or “design away” all potential ignition sources. Oxygen compatibility is defined as the ability of a material to coexist with oxygen and potential ignition sources with an acceptable, manageable degree of risk.

Transhab Materials Selection

MICHAEL PEDLEY

Johnson Research Center, Mail Code EM2
2101 NASA Road 1
Houston, TX 77058 USA
Phone: 281-483-8913
E-mail: michael.d.pedley1@jsc.nasa.gov

NASA Johnson Space Center is developing lightweight, inflatable space structures. Such structures offer significant advantages over traditional metal "cans," because their dimensions are not limited by the capacity of the launch vehicle and their weight is much lower. The Transhab vehicle has been considered a potential habitation module for the International Space Station crew and as a transport and habitation vehicle for a future mission to Mars.

The design of such large nonmetallic structures presents major materials challenges. They must be able to hold a 1-atmosphere pressure differential between the internal environment and space vacuum with a leak rate comparable to that of an aluminum structure. They must be deployable under a range of thermal conditions. After deployment, the structures must be able to withstand the effects of the low-Earth orbit environment (atomic oxygen, radiation, plasma, meteoroids, and debris) for approximately 15 years without significant degradation. Standard issues with nonmetallic materials in habitable flight compartments (flammability, toxic offgassing, fungus, and microbial growth) are magnified when the entire pressure wall is fabricated from such materials.

This paper describes the work conducted by the Transhab Project to solve these materials challenges and eliminate the risks associated with this novel design.

Identification of High-Performance, Low Environmental Impact Materials and Processes Using Systematic Substitution (SyS)

PATRICK M. DHOOGE and Jonathan S. Nimitz

Environmental Technology and Education Center (ETEC)
4500-B Hawkins St. NE
Albuquerque, NM 87109-4517 USA
Phone: 505-345-2707
Fax: 505-345-4884
E-mail: pdhooge@etec-nm.com
jnimitz@aol.com

Effective pollution prevention programs often require replacement of polluting substances or processes that produce pollution. These replacements often produce cost savings as well. ETEC has developed and successfully applied a method called Systematic Substitution (SyS) for identification of high-performance, low environmental impact materials and processes. The method is logical, thorough, and easily understood and has succeeded in several efforts to identify superior alternatives for problematic materials and processes.

Technical operations depend on a variety of materials and processes used in research, development, production, and facilities. Many of these materials and processes are sources of pollution that should be eliminated. In addition, materials in use for many years often become expensive or unavailable. Expensive materials continue to be used because they have always been used. Vendor alternatives that can be pressed into service as substitutes often do not perform as well, pose additional operational risks, require more elaborate equipment and procedures, and may themselves become scarce and expensive over time. The trend in emissions and waste regulations is toward tighter restrictions and higher costs. It is vital to be proactive in replacing problematic materials and processes in a cost-effective manner. If accomplished properly, eliminating pollution and waste reduces operational costs.

SyS uses a spreadsheet program to evaluate alternatives by the Weighted Ranking of Attributes Process (WRAP). The elements of SyS will be presented and a sample evaluation reviewed to illustrate the SyS method. The authors will also present several examples of successful high-performance, low environmental impact substitute materials and processes identified by SyS during projects at ETEC. Examples will include cleaning systems and solvents, a rocket thrust vector control fluid, the Space Shuttle cooling loop working fluid, and refrigerants.

Selection Criteria for Alternative Technologies as a Method of Hazardous Waste Minimization

ERIC LETHE

Inland Technology Incorporated
401 East 27th Street
Tacoma, WA 98421 USA
Phone: 253-383-1177
Fax: 253-593-8749
E-mail: inland@inlandtech.com

The need for environmentally responsible processes and products grows more pressing every day. As the need for these responsible alternatives grows, so grows the confusion in selecting the most appropriate materials or equipment. In the past, price and effectiveness were the guidelines by which products were procured for manufacturing processes. Today, the regulatory pressures on industrial America are forcing an examination of processes across the board. In many companies, the “environmental officer” is considered as important as the production manager or controller.

Environmental managers often are not chemists and, while schooled in the necessities of disposal laws, may not be knowledgeable in the areas necessary to supervise a search for alternatives. The examination of possible alternates is often left to the last moment and conducted by co-workers who may be less than enthusiastic about changes. In this climate, resistance to anything new is already in place before any suggestion has been made. Inevitably, such circumstances cause a “not acceptable” stamp to be placed upon any environmentally responsible alternative.

This presentation will suggest methods for selection of alternative products and processes without leaving you at the mercy of sales representatives. We will address:

- Process examination
- Material selection
- Possible impediments
- Steps to implementation
- How to avoid “snake oil” solutions and their risks.

We will focus on procedures that will assist you in your decision-making process for choosing alternatives and environmentally sound chemicals and equipment.

How to Reduce Costs and Improve Technical Risks

ROBERT P. HILL

Joint Group on Pollution Prevention
Kennedy Space Center/YA-E
Kennedy Space Center, FL 32899 USA
Phone: 407-867-8795
Fax: 407-867-8479
E-mail: Robert.Hill-3@kmail.ksc.nasa.gov

Michael McCall
Joint Group on Pollution Prevention
Concurrent Technologies Corporation
100 CTC Drive
Johnstown, PA 15904 USA
Phone: 814-269-2897
Fax: 814-269-6882
E-mail: mccall@ctc.com

The military services' Defense Logistics Agency (DLA) and NASA co-chartered the establishment of the Joint Group on Pollution Prevention (JG-PP). The JG-PP's executive guidance is to continue the reduction or elimination of hazardous materials (HAZMATs) by establishing partnerships to foster cooperation, leverage limited resources, avoid duplication of effort, and reduce total cost of ownership. This effort is expected to result in changes to design, manufacturing, and maintenance processes that are cleaner, faster, cheaper, and less hazardous. The Joint Acquisition-Sustainment Pollution Prevention Activity (JASPPA) is responsible for accomplishing executive program direction and project execution.

The JG-PP provides engineering, technical, and business services required to identify and accomplish validated pollution prevention projects. The JASPPA will facilitate projects by establishing partnerships among industry contractors, affected Army, Navy, Marine Corps, and Air Force weapon system program managers, depot process owners, NASA Center and enterprise managers, and the Defense Contract Management Command (DCMC). These partnerships will identify and validate alternatives to HAZMATs usage through the Acquisition Pollution Prevention Initiative (AP2I). Once engineering authorities have validated an alternative, the industry contractor uses the Single Process Initiative (SPI) block change to modify contracts for implementation across all affected systems and components. Depot maintenance activities will utilize their respective service/agency change mechanism for implementation.

JG-PP project findings are made available to government and industry for future use on pollution prevention opportunities. To assist in making findings available, the JG-PP has established a web site at www.jgpp.com.

In conclusion, the JG-PP effort reduces HAZMAT use, increases technical confidence, provides cost avoidance/savings, and minimizes use of multiple material specifications at industry contractor and government facilities.

Liquid Filtration for Component Reliability and Waste Minimization

BARBARA KANEGSBERG and Edward Kanegsberg

BFK Solutions
16924 Livorno Drive
Pacific Palisades, CA 90272 USA
Phone: 310-459-3614
Fax: 310-459-3624
E-mail: BKanegsberg@compuserve.com

Appropriate filtration results in benefits for pollution prevention, product quality, and economics. Filtration is often required to minimize contaminants in both organic and aqueous-based cleaning agents. Failure to perform adequate filtration can compromise performance, in some cases leading to catastrophic product failure. Filtration can also be used to extend the life of the cleaning agent and to minimize waste stream volume. This represents favorable economic and ecological impacts.

Appropriate filtration, particularly for critical cleaning applications, is in the process of being developed. Filtration can be used to remove particles and suspended or dissolved solids. There is, however, particularly with ultrafiltration, the potential to deplete the cleaning agent itself.

The presentation will cover filtration before, during, and after the cleaning process. Techniques to be discussed include mechanical, adsorptive, deionization, and reverse osmosis. The benefits, limitations, and on-going development of various filtration approaches will be discussed.

Chemical Aging of Environmentally Friendly Cleaners

L.L. BIEGERT, K.B. Evans, B.D. Olsen, and B.L. Weber

Cordant Technologies, Thiokol Propulsion
P.O. Box 707, M/S 243
Brigham City, UT 84302-0707 USA
Phone: 435-863-3958
E-mail: biegell@thiokol.com

Use of cleaners in the manufacturing area demands bottles that will hold a sufficient amount of material and allow for easy and controlled dispensing by the operator without contamination or material leaching from the bottle. Manufacturing storage conditions are also a factor that may affect cleaner chemical integrity and its potential to leave a residue on the part.

A variety of squeeze bottles stored in mild (72 °F, 10% RH, dark) and harsh (105 °F, 50% RH, fluorescent lighting) conditions were evaluated to determine the effect of environment and bottle exposure on the ozone depleting chemical cleaner's chemical composition. Low Density Polyethylene (LDPE) bottles were found to be quite permeable to all the cleaners evaluated in this study, indicating this bottle type should not be used in the manufacturing area. Fluorinated Polyethylene (FLPE) bottles showed little cleaner loss and change in cleaner chemical composition over time, suggesting these bottles would be acceptable for use.

Chemical analysis indicates limonene-containing cleaners show increased non-volatile residue (NVR) content with storage under harsh conditions. Some cleaners use butylated hydroxytoluene (BHT) as a stabilizer and to protect against limonene oxidation. Under harsh conditions, BHT was quickly depleted, resulting in higher NVR levels.

National Advanced Materials Information System

JEFF GUTHRIE

AMPTIAC
201 Mill St
Rome, NY 13440 USA
Phone: 315-339-7058
Fax: 315-339-7107
E-mail: jguthrie@iitri.org

The following paper describes the National Advanced Materials Information System (NAMIS) developed by the Advanced Materials and Processes Technology Information Analysis Center (AMPTIAC).

NAMIS preserves the Department of Defense materials and process knowledge base, making it readily available to the materials community. Inside NAMIS, users will find three database modules of interest to the high-temperature materials community. Two searchable bibliographic databases containing all past High Temperature Workshop proceedings and the Cocoa Beach Conference have individual paper citations linked by viewable electronic documents. The third database module, NASP, contains a virtual library of all the National AeroSpace Plane final reports from the materials and structures augmentation program.

Although the NASP program never came to fruition, many breakthroughs in high-temperature materials and processes owe their success to the NASP program. Since NASP never was fielded, these breakthroughs in materials often never fully transitioned, and eventually the technical heritage and expertise dissipated. Both government and industry personnel moved away from high-temperature materials problems, and often their personnel libraries were lost.

Today, many proposed new systems present similar technical challenges and require this same expertise. For example, NASA's X-33, X-34, Reusable Launch Vehicle, Hyper X, and Future X will need advanced thermal protection systems (TPSs), hot structures, and huge liquid hydrogen and liquid oxygen tanks. In the military, the Military Space Plane will require these same technologies. Additionally, multiple new missile concepts, such as the Common Aero Vehicle, the Hypersonic Technology program, and the High Speed Strike program, demand innovative hot structure and TPS.

AMPTIAC will demonstrate the features of these web-based databases, which are found at the following URL: http://NAMIS.iitri.org/

Durability Characterization of Advanced Polymeric Composites at Cryogenic Temperatures

THOMAS S. GATES

Mechanics and Durability Branch/Mail Stop 188E
Langley Research Center
Hampton, VA 23681 USA
Phone: 757-864-3400
Fax: 757-864-7729
E-mail: T.S.Gates@larc.nasa.gov

The next generation of reusable launch vehicles will require technology development in several key areas. Of these key areas, the development of polymeric composite cryogenic fuel tanks promises to present one of the most difficult technical challenges. It is envisioned that a polymer matrix composite (PMC) tank would be a large shell structure capable of containing cryogenic fuels and carrying a range of structural loads. The criteria that will be imposed on such a design include reduced weight, conformal geometry, and impermeability. It is this last criterion, impermeability, that will provide the focus of this paper.

The essence of the impermeability criterion is that the tank remains leak free throughout its design lifetime. To address this criterion, one of the first steps is to conduct a complete durability assessment of the PMC materials. At Langley Research Center, a durability assessment of promising new polyimide-based PMCs is underway. This durability program has focused on designing a set of critical laboratory experiments that will determine fundamental material properties under combined thermal-mechanical loading at cryogenic temperatures. The test program provides measurements of lamina and laminate properties, including strength, stiffness, and fracture toughness. The performance of the PMC materials is monitored as a function of exposure conditions and aging time. Residual properties after exposure are measured at cryogenic temperatures and provide quantitative values of residual strength and stiffness. Primary degradation mechanisms and the associated damage modes are measured with both destructive and nondestructive techniques. In addition to mechanical properties, a range of physical properties, such as weight, glass transition, and crack density, are measured and correlated with the test conditions. This paper will report on the progress of this research program and present critical results and illustrative examples of current findings.

Development of Metal Matrix Composites for NASA's Advanced Propulsion Systems

JONATHAN A. LEE

Marshall Space Flight Center/ED33
Huntsville, AL 35812 USA
Phone: 256-544-9290
Fax: 256-544-5877
E-mail: Jonathan.A.Lee@msfc.nasa.gov

Sandy Elam
Marshall Space Flight Center/TD61
Huntsville, AL 35812 USA
Phone: 256-544-8902
Fax: 256-544-2032
E-mail: Sandra.K.Elam@msfc.nasa.gov

In this paper, the state-of-the-art development of metal matrix composites (MMCs) for NASA's advanced propulsion systems will be presented. The paper will focus on key MMC materials that will provide a high payoff for NASA's Reusable Launch Vehicle (RLV) systems and space access vehicles. These materials are lightweight, affordable, and environmentally compatible with oxygen and hydrogen. Historically, MMCs have been used for NASA's flight hardware, such as the boron-aluminum struts for the Space Shuttle's mid-fuselage and the graphite-aluminum antenna for the Hubble Space Telescope. In recent years, Marshall Space Flight Center has focused on the development of low-cost and lightweight MMC components for advanced liquid fuel rocket engines. Significant investments and advances have been made in the design, analysis, and manufacturing of candidate RLV propulsion hardware, such as liquid hydrogen and oxygen turbopump housings, fuel line ducts, flanges, and structural jackets for combustion chambers. Lesson learned and future directions for MMC technology will be presented.

Inorganic-Organic Hybrid Polymers for High-Temperature Aerospace Applications

TEDDY M. KELLER

Chemistry Division, Code 6127
Naval Research Laboratory
4555 Overlook Ave. S.W.
Washington, DC 20375-5320 USA
Phone: 202-767-3095
Fax: 202-767-0594
E-Mail: keller1@ccf.nrl.navy.mil

An emerging technology that holds promise for extending the temperature stability of polymers is inorganic-organic hybrid polymers. In our continuing investigations of high-temperature polymers at the Naval Research Laboratory, linear siloxane-acetylenic and carborane-siloxane-acetylenic polymers have been synthesized and are being evaluated as high-temperature matrix materials for composites up to 510 ˚C (950 ˚F) and as precursor materials for ceramic applications up to 1500 ˚C (2732 ˚F) in air. The major advantage of our approach is that the desirable features of inorganics and organics, such as high thermal and oxidative stability and processability, are incorporated into the same polymeric chain. The chemistry involved in synthesizing poly(siloxane) and poly(carborane-siloxane) has been modified to accommodate the inclusion of an acetylenic unit in the backbone. The siloxane units provide thermal and chain flexibility to polymeric materials. The acetylene group remains inactive during processing at lower temperatures and reacts either thermally or photochemically to form conjugated polymeric cross-links without the evolution of volatiles. Siloxane-acetylenic polymers lack the thermal and oxidative stability that the carborane-siloxane-acetylenic systems possess upon conversion to thermosets and ceramics. Co-polymers containing various compositions of the poly(siloxane-acetylene) and poly(carborane-siloxane-acetylene) units have been synthesized and evaluated. Similar polymeric mixtures relative to the co-polymers can be obtained by blending various amounts of poly(siloxane-acetylene) and poly(carborane-siloxane-acetylene). The novel linear polymers have the advantage of being extremely easy to process and convert into thermosets or ceramics, since they are either liquids at room temperature or low melting solids.

The linear siloxane-acetylenic and carborane-siloxane-acetylenic polymers provide advanced structural materials (thermosets and ceramics) for applications in excess of 1,000 ˚C in an oxidizing environment. These novel inorganic-organic hybrid polymers represent a major technological breakthrough in the design of polymers and ceramics for applications under extreme environmental conditions. These advanced materials could potentially be used in the fabrication of advanced ceramic fibers and as high-temperature, high-performance structural materials for extraterrestrial vehicles, such as the next generation Space Shuttle, reusable launch vehicles/boosters, nuclear and fusion power generation, high-performance heat engines, gas turbine engines, heat exchangers, cutting tools, coatings to protect carbon/carbon composites against oxidation, high-temperature adhesives, medical devices, brake linings for aircraft, and electronic applications.

Integrated High-Payoff Rocket Propulsion Technologies Program Materials Development Plan

R. G. CLINTON, JR.

Marshall Space Flight Center/ED34
Huntsville, AL 35812 USA
Phone: 256-544-2682
Fax: 256-544-2825
E-mail: Corky.Clinton@msfc.nasa.gov

Brian Reed
Glenn Research Center
21000 Brookpark Road
Cleveland, OH 44135 USA

Michael Stropki, Dan Cleyrat, Brian Stucke, and Shawn Phillips
Air Force Research Laboratory
Wright-Patterson Air Force Base, OH 45433 USA

The Integrated High-Payoff Rocket Propulsion Technology (IHPRPT) Program is a joint Department of Defense, NASA, and industry effort to improve the nation's rocket propulsion capabilities dramatically. This phased program is structured with increasingly challenging goals focused on performance, reliability, and cost to double rocket propulsion capabilities by 2010. The IHPRPT Program is focused on three propulsion application areas: boost and orbit transfer (both liquid rocket engines and solid rocket motors), tactical, and spacecraft. Critical to the success of this initiative is the development and application of advanced materials, processes, and manufacturing technologies. To meet this challenge, the IHPRPT Materials Working Group (IMWG) was chartered with the responsibility to establish a plan for the development of these technologies, which are enabling for the rocket propulsion community to achieve the IHPRPT goals.

The IMWG materials plan and execution approach have been approved by the IHPRPT Steering Committee. Implementation activities are in progress, and a research announcement will be issued. The presentation will provide an overview of the materials plan, a status of the research initiation efforts, and a look at the future plans for the IMWG.

International Space Station Manufacturing

TODD MAY

Johnson Space Center/Code OB
2101 NASA Road 1
Houston, TX 77058 USA
Phone: 256-961-1769
Fax: 256-544-5760
E-mail: todd.a.may1@jsc.nasa.gov
tmay@ems.jsc.nasa.gov
todd.may@msfc.nasa.gov

Building major elements of the International Space Station is indeed a daunting task. The standard challenges of integrating aerospace hardware apply; however, these difficulties are compounded with complex relationships with international partners, industry partners and suppliers, and government customers and suppliers. Staggered development schedules add another level of complexity. In this environment, success is dependent on meticulous planning. Every detail of manufacture, assembly, and test must be considered, and a comprehensive plan must be generated, which establishes progress and makes necessary adjustments. This presentation examines the process of establishing this plan and its necessary components.

Careful planning, by itself, will not guarantee success, however. One must anticipate problems with it plan execution and be ready and willing to make appropriate course adjustments. This presentation also examines several real challenges that have required plan adjustments, with an emphasis on lessons learned to prepare the audience to anticipate problems in future endeavors.

Findings from the X-33 Hydrogen Tank Failure Investigation

MINDY NIEDERMEYER

Marshall Space Flight Center/TD70
Huntsville, AL 35812 USA
Phone: 256-544-1569
Fax: 256-544-9358
E-mail: Melinda.W.Niedermeyer@msfc.nasa.gov

The X-33 hydrogen tank failed during test in November of 1999 at MSFC. The tank completed the structural loading phase of the test successfully and was drained of hydrogen before the failure. The failure initiated in the acreage of Lobe 1 and instantaneously peeled the outer skin and core from the inner skin. There were several factors that provided the opportunity for the tank to fail in this way. The factor giving life to these opportunistic circumstances was hydrogen infiltration into the core of the tank. The mechanism for this phenomenon will be discussed in this presentation.

Assessment of the State of the Art in the Design and Manufacturing of Large Composite Structures

CHARLES E. HARRIS

Center of Excellence for Structures and Materials
Langley Research Center/Mail Stop 121
Hampton, VA 23681-2199 USA
Phone: 757-864-3447
Fax: 757-864-7729
E-mail: C.E.Harris@larc.nasa.gov

An assessment of the state of the art in the design and manufacture of large composite structures has been prepared by the Center of Excellence for Structures and Materials. The preparation of the assessment was in response to an action item from the NASA Associate Administrator for Aero-Space Technology. The background motivating the action item was a series of unexpected manufacture and design problems with the composite structures of the X-33 and X-34 experimental aircraft. These experimental aircraft will fly at hypersonic speeds to better understand the technology challenges required to develop a single-stage-to-orbit reusable launch vehicle to replace the Space Shuttle. The focus of the assessment is large structural components, such as those in commercial and military aircraft and space transportation vehicles. (Turbomachinery components and ceramic and metal matrix composites are not included in this assessment.)

The baseline for the assessment is the historical evolution of composites in actual aerospace vehicles. The assessment emphasizes the application of structural composites in moderately to heavily loaded aerospace vehicles. Applications of composites are reviewed for large commercial transport aircraft, general aviation aircraft, rotorcraft, military fighter aircraft, and military transport aircraft. The baseline also includes the application of composites in unmanned rockets and space transportation vehicles. The assessment of the state of the art includes a summary of lessons learned, examples of current practice, and an assessment of advanced technologies under development. The assessment concludes with an evaluation of the future technology challenges associated with applications of composites to the primary structure of commercial aircraft and advanced space transportation vehicles.

A Mass Spectrometer-Based Tool for In-Process Analysis of RSRM Components

MICHAEL MELTZER

Lawrence Livermore National Laboratory/L-627
7000 East Avenue
Livermore, CA 94550-9234 USA
Phone: 925-424-6923
Fax: 925-422-4038
E-mail: meltzer1@llnl.gov

Carolyn Koester
Lawrence Livermore National Laboratory/L-542
7000 East Avenue
Livermore, CA 94550-9234 USA
Phone: 925-422-6888
Fax: 925-423-7998
E-mail: koester1@llnl.gov

Neil Sagers
Thiokol Propulsion
231 N. Burns
Ogden, UT 84404 USA
Phone: 435-863-6116
Fax: 435-863-5509

Work to date is reported for a project testing the capabilities of a mass spectrometer-based system for analyzing *in-situ* organic compounds on a variety of substrates. The system, which was built at Lawrence Livermore National Laboratory, is termed a Contamination Analysis Unit (CAU) and employs vacuum and thermal desorption of surface residues, followed by ionization and analysis with a Leybold Inficon Transpector mass spectrometer. The CAU was employed in this study to examine soils, cleaner residues, and substrates on Space Shuttle Reusable Solid Rocket Motor (RSRM) components. Project work was supported by Thiokol Propulsion. Major project objectives include:

1. Determine if the CAU can detect solvent that has soaked into NBR insulation material
2. Test the capabilities of the CAU for analyzing non-flat surfaces on the inside and outside surfaces of the RSRM and nozzle throat housing
3. Determine if solvent extraction and gas chromatography approaches are able to enhance the surface analysis data available through use of the mass spectrometer-based CAU
4. Determine the CAU's detection limit for various RSRM soils and cleaners
5. Determine if contact of either Viton® or silicon O-rings with critical substrates will result in any visual evidence of the contact, when observed under black light.
6. Demonstrate CAU viability during routine RSRM manufacturing operations.

Structural Adhesive Systems Cured at Moderate Temperatures (120-130 °C)

.
FU CHUNMING

Kuang Hong Fu Gang
(The Petrochemical Research Institute of Heilongjiang Province)
164 Zhongshan Avenue
Harbin 150040, People's Republic of China

The structural adhesive systems J-47, J-69, and J-159 can be cured at moderate temperatures (120 to 130°C) with use temperature limitations of 120 °C, 100 °C, and 150 °C, respectively. These structural adhesive systems have been used to bond sheet-to-sheet or skin-to-honeycomb sandwich cores of aluminum alloy, titanium alloy, and carbon-fiber reinforced epoxy composites. These various structural components have been applied successfully to satellites, rockets, airplanes, trains, subways, advertising boards, and architectural curtain walls for 15 years. The properties of these adhesives are listed in the following table:

Adhesive Name	Use Temperature Range	Shear Strength MPa		Peel Strength N/cm	
				Skin to Sheet	Skin to Honeycomb
J-47 A,B,C,D	-180 °C to 100°C	23 °C >30	100 °C >15	>50	>40
J-69 A,B,C,D	-60 °C to 80 °C	23 °C >30	80 °C >18	>50	>40
J-159 A,B,C,D	-60 °C to 150 °C	23 °C >28	150 °C >15	>40	>30

A: film, bonded sheet or skin to sheet
B: primer
C: film, bonded sheet or skin-to-honeycomb sandwich core
D: foam tape (skin thickness 0.3 mm)

Effects and Detection of Silicone and HD2 Grease Contaminants

JERRELL W. BLANKS

Thiokol Propulsion Group
P.O. Box 9033
Marshall Space Flight Center/Building 4712
Huntsville, AL 35812 USA
Phone: 256-544-7899
E-mail: blankjw@thiokol.com

The bond integrity of Reusable Solid Rocket Motor bond systems can influence the overall system safety. Evaluated was the minimum level of different contaminants, especially silicone oils, present before various bond systems are weakened. Application of an infrared spectrometer was used to detect and quantify sets of contaminants on selected composites and metal substrates. Techniques for applying the contaminants will be discussed. Changes occurring with time at the contaminant/substrate interface were monitored. Use was made of these techniques to prepare bond specimens for determining the lowest level of common contaminants that are detrimental to selected bond systems.

Physical Evaluation of Cleaning Performance – We Are Only Fooling Ourselves

EARL PRATZ

Lockheed Martin Michoud Space Systems
P.O. Box 29304, M/S 4710
Michoud Assembly Facility
New Orleans, LA 70189 USA
Phone: 504-257-1761
Fax: 504-257-4438
E-mail: Earl.H.Pratz@maf.nasa.gov

Surface cleaning processes are normally evaluated using visual physical properties, such as streaking, staining, and water-break-free conditions. There is the assumption that these physical methods will evaluate all surfaces all the time for all operations. We have found that these physical methods are lacking in sensitivity and selectivity with regard to surface residues and subsequent process performance. We will report several conditions where evaluations using visual physical properties are lacking. We will identify possible alternative methods and future needs for surface evaluations.

Low Environmental Impact, High-Performance Foam Blowing Agents Based on Iodofluorocarbons

PATRICK M. DHOOGE, Suzanne M. Glass, and Jonathan S. Nimitz

Environmental Technology and Education Center (ETEC)
4500-B Hawkins St., NE
Albuquerque, NM 87109-4517 USA
Phone: 505-345-2707
Fax: 505-345-4884
E-mail: pdhooge@etec-nm.com
jnimitz@aol.com

Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) have been used for many years as high-performance, polymer foam blowing agents because of their physical properties, stability, relatively high molecular weight, and low toxicity. These blowing agents, however, deplete stratospheric ozone and have been (or will soon be) phased out of production in developed countries under the provisions of the Montreal Protocol and its amendments. To address the need for new high-performance, low atmospheric impact foam blowing agents, ETEC has investigated the family of iodofluorocarbons (IFCs), which have been identified as having very low atmospheric impact and some attractive physical properties, to replace CFCs and HCFCs. U.S. and international patents were filed to protect the IFC foam blowing technology. Theory and previous experiment results with other foam blowing agents show that, if properly formulated, foams blown with CF_3I should have 15 to 20% better insulating ability than foams blown with HCFC-141b and HCFC-142b. Also, since CF_3I has a significantly greater molecular weight, it will diffuse out of the foam much more slowly, giving foams blown with CF_3I much better aging characteristics. Because of their superior insulating ability, polymer foams blown with IFC-based agents would allow lighter weight and lower volume insulation, significantly improving aerospace system performance.

IFCs considered included CF_3I, C_2F_5I, 1-C_3F_7I, and 2-C_3F_7I. Blends of CF_3I with hydrofluorocarbons (HFCs) and with carbon dioxide were also investigated. Closed-cell test foams were prepared from polyurethane and polyethylene. Selected properties of the test foams were measured, including density, strength, thermal conductivity, and flammability. Detailed results of the foam preparation and testing will be presented. Polyethylene foams prepared with CF_3I and blends showed strengths and thermal conductivities essentially equal to, and were significantly less flammable than, the same foams prepared with HCFC-142b. The expected increased insulating ability was not seen in these preliminary trials. Problems were encountered with polymer precursor solubility in CF_3I and its blends. Further investigations of polymer component solubilities to optimize polymer compositions and blowing agent dispersion and measurements of cell interconnectivity in prepared foams are needed to provide the best chance to attain the improved insulating ability that should be possible with the CF_3I-based blowing agents. The potential cost savings in aerospace applications are many times the development costs.

Update: HFC 245fa Blown Foam Development with External Tank Spray Foams

SIMON DAVIS

Lockheed Martin Manned Space Systems
Marshall Space Flight Center/Bldg. 4739
Huntsville, AL 35812 USA
Phone: 256-544-6482
Fax: 256-544-2774
E-mail: Simon.Davis@msfc.nasa.gov

The MSFC Thermal Protection Systems (TPS) Materials Research Laboratory is currently investigating environmentally friendly blowing agents for use in the insulations of the Space Shuttle's External Tank. The original TPS foam materials of the External Tank were blown with chlorofluorocarbon 11, which is now regulated because of its high Ozone Depletion Potential (ODP). Hydrochlorofluorocarbons (HCFCs), with an ODP that is one tenth that of CFCs, have been widely adopted as an interim blowing agent in urethane insulations. In FY96, Lockheed Martin completed the production qualification and validation of HCFC 141b blown insulations. Because of the expected limited commercial lifetime of HCFC 141b, research efforts are underway to identify and develop alternatives with zero ODP. HFC 245fa (1,1,1,3,3 pentaflouropropane) has been chosen by the manufacturer as a third-generation blowing agent to be marketed commercially. Preliminary work evaluating this third-generation candidate has demonstrated promising material mechanical property data. Favorable results from small-scale spray activities have justified evaluations using production foam processing spray parameters. With the scale-up of the spray equipment, however, additional processing issues have been identified. This paper will present data collected to date regarding the use of this blowing agent in External Tank spray foams.

High-Performance, Low Environmental Impact Refrigerants

PATRICK M. DHOOGE, Edward T. McCullough, Suzanne M. Glass, and Jonathan S. Nimitz

Environmental Technology and Education Center (ETEC)
4500-B Hawkins St., NE
Albuquerque, NM 87109-4517 USA
Phone: 505-345-2707
Fax: 505-345-4884
E-mail: pdhooge@etec-nm.com
jnimitz@aol.com

High-performance chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants, including R-12 and R-22, which have enjoyed widespread use, have been (or soon will be) phased out of production in developed countries under the provisions of the Montreal Protocol and its amendments. Substitute refrigerants that may be pressed into service often pose flammability or toxicity risks, have lower energy efficiency or capacity, or may themselves be scheduled for phase-out (as with the HCFCs). To help in replacing CFC and HCFC refrigerants, ETEC has developed three new high-performance, low environmental impact refrigerants, designated Ikon® A, B, and C. Development of Ikon® B and Ikon® C has been funded by Kennedy Space Center. The new refrigerants, covered under extensive U.S. and international patents, are near-azeotropic blends containing the compound CF_3I. They are energy-efficient, nonflammable, non-ozone-depleting, low global warming, relatively low toxicity, stable in refrigeration and air conditioning systems, and compatible with common refrigeration system materials of construction. Ikon® A and Ikon® B are replacements for medium pressure refrigerants such as R-12 and R-134a. Ikon® C has been developed as a direct replacement for R-22.

Ikon® A and Ikon® B have been used as drop-in replacements for R-12 and R-134a in a water chiller, a 20-ton air conditioning unit, refrigerated transports, and a domestic refrigerator. Ikon® C has been used as a replacement for R-22 in a water chiller. The performances of Ikon® B and Ikon® C have also been measured independently in Oak Ridge National Laboratory's (ORNL's) Vapor Compression Test Loop.

Results show that Ikon® A and Ikon® B have 10 to 20% higher energy efficiency and approximately 15% greater volumetric cooling capacity than R-12 and R-134a. Estimates of energy savings indicate that the Ikon® refrigerants will typically repay their cost of installation in 1 to 3 years, dependent on average system loading and electricity cost. Results of Ikon® C testing show that, in a water chiller, it has 95% the cooling capacity and 98% the energy efficiency of R-22, with almost exactly the same operating pressures and only about 1 K (2 °F) greater temperature glide through the evaporator. The independent testing at ORNL confirms the water chiller results.

Volatile Organic Compound Compliant Wax Removal Process

ALAN BROWN, David Grimmett, and Margarite Sylvia

The Boeing Company
Rocketdyne Propulsion and Power
6633 Canoga Avenue
Canoga Park, CA 91309-7922 USA
Phone: 818-586-6636
Fax: 818-586-7219
E-mail: Alan.Brown@West.Boeing.com

Wax is often used as a maskant during plating operations to protect against unwanted deposits on hardware details. Historically, perchloroethylene was used to remove this wax at the completion of the plating operation. In 1994, perchloroethylene was eliminated from this process at Rocketdyne and was replaced by a high-temperature oil and a cleaning process based on a semi-aqueous cleaner. This semi-aqueous cleaner has a volatile organic content of 768 g/l, and environmental management of this material has limited the location of the operation. It was, therefore, desirable to identify a replacement cleaner not subject to these limitations, enabling the process to be located in closer proximity to the other manufacturing areas processing the hardware. This would result in the elimination of transportation of the hardware, the schedule impact of moving it, and the risk associated with additional handling. A cleaner was identified that satisfied these requirements, and Taguchi methodology was used to optimize the process using this material.

Highly Effective, Low-Toxicity, Low Environmental Impact Total Flooding Fire Suppressants

PATRICK M. DHOOGE, Suzanne M. Glass, and Jonathan S. Nimitz

Environmental Technology and Education Center (ETEC)
4500-B Hawkins St., NE
Albuquerque, NM 87109-4517 USA
Phone: 505-345-2707
Fax: 505-345-4884
E-mail: pdhooge@etec-nm.com
jnimitz@aol.com

Production of halon fire suppressants, such as halon 1301, has been banned in developed countries under the provisions of the Montreal Protocol and its amendments regulating production of ozone-depleting substances. Available gaseous substitutes, such as HFC-227ea and HFC-125, are not as effective, resulting in large retrofit costs to install larger systems, and significant weight and volume penalties in aircraft and spacecraft. In most aerospace applications, water or solid agents cannot be used. Carbon dioxide has been pressed into service as a fire suppressant in some applications, but its effective fire suppression level (29%) is higher than the concentration that causes almost immediate death in humans (27%).

To help in replacing total flooding halon fire suppressants, ETEC has investigated a variety of compounds and blends; these hold promise of being as or more effective per weight than halon 1301, have minimal toxic effects, and have low environmental impact. One compound considered was CF_3I, a combustion suppression agent with effectiveness similar to halon 1301. CF_3I is gaining some wider acceptance. Somewhat unexpected results from combustion suppression testing of CF_3I on various gaseous fuels will be presented. Also presented will be results of flammability testing of the higher molecular weight iodofluorocarbons.

ETEC's investigations strongly indicate that blends of particular compounds have the best chance of meeting all of the goals for an acceptable halon 1301 replacement. Several proprietary combinations of low environmental impact gaseous compounds have been tested for their ability to suppress inert fuels and at least one appears to be as, or even more, effective than halon 1301. At their effective concentrations, predicted toxicity of the blends is within safe limits for human exposure. Selected results of these studies will be presented.

Promoted Combustion of Metals in a High-Pressure, Flowing Oxygen Environment

MIGUEL J. MAES

Johnson Space Center
White Sands Test Facility/MS 201LD
P.O. Box 20
Las Cruces, NM 88004 USA
Phone: 505-524-5677
E-mail: miguel.maes1@wstf.nasa.gov

Joel M. Stoltzfus
Johnson Space Center
White Sands Test Facility/ MS RF1
P.O. Box 20
Las Cruces, NM 88004 USA
Phone: 505-524-5731
Fax: 505-524-5260
E-mail: joel.m.stoltzfus1@wstf.nasa.gov

Traditional promoted combustion testing has used 1/8-in. diameter samples that are ignited in a pressurized, oxygen-enriched environment. Many years of testing this sample size have yielded useful data regarding the threshold pressure, or the minimum oxygen pressure required to support self-sustained combustion. When a material is tested in a flowing system, however, the threshold pressure changes. White Sands Test Facility has developed a test system to burn samples in flowing gaseous oxygen. The pressures can range up to 2,000 psi with gas velocities reaching 200 ft/s. Aluminum, carbon steel, and 304 stainless steel 1/2-in. diameter rods were tested to demonstrate system compatibility. This paper provides a description of the apparatus used, the test method, and the results.

Problem Solving Applications of Chemical Fingerprinting

MICHAEL O. KILLPACK, Dennis J. Fife, Chad R. Saunders, Charles R. Whitworth, and William H. McClennen

Thiokol Propulsion, Analytical Laboratories
P.O. Box 707, M/S 245
Brigham City UT 84302-0707 USA
Phone: 435-863-3511

Good manufacturing processes are dependent on the ability to foresee, reduce, or quickly resolve problems critical to the quality and consistency of the end product. Thiokol has initiated a chemical fingerprinting program in conjunction with NASA, designed to identify and mitigate such manufacturing problems through a better understanding of the base materials. An historical database with real-time access maintained by a core of material specialists is an essential problem-solving tool. This “fingerprinting process” will be discussed in terms of identification of critical materials and analysis techniques, development of a comprehensive database, coordination and concerns of vendors, and actual examples where fingerprinting has been used to reduce and resolve problems.

Resources Available for Hazards Analysis of Aerospace Fluids

STEPHEN S. WOODS

Allied Signal Technical Services Corporation
White Sands Test Facility
P.O. Box 20, MS 201LD
Las Cruces, NM 88004 USA
Phone: 505-524-5607
Fax: 505-524-5260
E-mail: stephen.s.woods1@wstf.nasa.gov

Walter F. Stewart
L&M Technologies, Inc.
4209 Balloon Park Rd. NE
Albuquerque, NM 87109-5802 USA
Phone: 505-343-0200
Fax: 505-343-0300

David L. Baker and Harold Beeson
Johnson Space Center
White Sands Test Facility
P.O. Box 20
Las Cruces, NM 88004 USA
Phone: 505-524-5605
Fax: 505-524-5260
E-mail: david.l.baker1@wstf.nasa.gov
harold.d.beeson1@wstf.nasa.gov

The effects of the rapid transfer of government functions to the aerospace industry, combined with those of aerospace corporate mergers, have the potential for disrupting coordination and flow of vital propellant safety and hazards information among designers, operations personnel, and safety personnel. Coinciding with these changes are new laws, such as the National Technology Transfer Act, designed to accelerate technology transfer to industry and promote government-industry partnership. The White Sands Test Facility (WSTF) has developed initiatives to help meet these needs and to coordinate the exchange of NASA's propellant hazards and safety information with industry. This is being done through the development of consensus, guidelines, propellant hazards analysis protocols, and safety courses for the propellant use of hydrogen, oxygen, and hypergols. Work in progress includes the transition of *NASA's Safety Standard for Oxygen and Oxygen Systems* to an American Society for Testing and Materials (ASTM) manual and the development of *NASA's Safety Standard for Hydrogen and Hydrogen Systems* as an American Institute of Aeronautics and Astronautics (AIAA) consensus document. The WSTF hazards manuals *Fire, Explosion, Compatibility, and Safety Hazards of Hydrazine* and *Fire, Explosion, Compatibility, and Safety Hazards of Monomethylhydrazine* are also under development as AIAA consensus documents. An effort is also underway to create an international standard on hydrogen safety through the International Organization for Standardization (ISO). For several years, WSTF has disseminated oxygen hazards information and expertise with the ASTM Oxygen Safety Course and the WSTF-developed Oxygen Hazards Analysis Protocol. Similar bodies of information are under development for hydrogen and hypergols. This information constitutes a valuable resource organized for the aerospace industry. For maximum benefit, industry must participate through the technical committees of the voluntary standards organizations chartered to manage this information. This paper presents these initiatives and seeks to inform the aerospace community of available resources and to promote involvement of industry partners.

Chemical Fingerprinting of Materials Developed due to Environmental Issues

DORIS A. SMITH, Mary Capezza, Emile Evans, and Laurie Rando

Lockheed Martin Space Systems, Michoud Operations
P.O. Box 29304
Michoud Assembly Facility
New Orleans, LA 70189 USA
Phone: 504-257-0228
E-mail: Doris.A.Smith@maf.nasa.gov

Instrumental chemical analysis methods are developed and used to chemically fingerprint new and modified External Tank materials made necessary by changing environmental requirements. Chemical fingerprinting can detect and diagnose variations in material composition. To characterize each material chemically, fingerprint methods are selected from an extensive fingerprint toolbox based on the material's chemistry and the ability of specific methods to detect the material's critical ingredients. Fingerprint methods have been developed for a variety of materials, including thermal protection system foams, adhesives, primers, and composites.

Use of GC/MS and Microtome Techniques to Evaluate ODC Cleaner Diffusion and Evaporation in Insulation and Phenolic Case Material

L.L. BIEGERT

Cordant Technologies, Thiokol Propulsion
P.O. Box 707, M/S 243
Brigham City, UT 84302-0707 USA
Phone: 435-863-3958
E-mail: biegell@thiokol.com

Because of the 1990 Clean Air Act Amendment, many chlorinated solvents used in the aerospace industry are being phased out. Replacement of the ozone-depleting chemicals (ODCs) with less volatile, non-ozone depleting cleaners has been extensively studied over the past 7 years at Cordant Technologies, Thiokol Propulsion.

The down selection of ODC replacement cleaners has been based on several factors, including the diffusion/evaporation of the cleaners in selected substrates. Methodologies were developed to evaluate the cleaner content in substrates. Methods of cutting thin slices of material (microtoming) were combined with gas chromatography/mass spectroscopy (GC/MS) analysis.

Substrates evaluated in this study include potential solid rocket motor materials: asbestos-filled nitrile butadiene rubber (ASNBR), carbon-filled ethylene propylene dimonomer (CFEPDM) insulation, and glass, carbon, and silica cloth phenolic (GCP, CCP, and SCP) substrates with fibers either parallel (0°) or perpendicular (90°) to the surface. Residue profiles indicate both cleaner and substrate composition affect the diffusion and subsequent evaporation of the cleaner from the substrate surface.

Electron Beam-Cure Polymer Matrix Composites: Processing and Properties

GEORGE WRENN and Barbara Frame

Oak Ridge National Laboratory
One Bethel Valley Road
P.O. Box 2009
Oak Ridge, TN 37831 USA
Phone: 423-241-2521 (Wrenn), 423-576-1892 (Frame)
Fax: 423-574-8257
E-mail: wrenngejr@y12.doe.gov
framebj@y12.doe.gov

Brian Jensen
Langley Research Center/Mail Stop 226
Hampton, VA 23681-2199 USA
Phone: 757-864-4271
Fax: 757-864-8312
E-mail: B.J.Jensen@larc.nasa.gov

Alan Nettles
Marshall Space Flight Center/ED34
Huntsville, AL 35812 USA
Phone: 256-544-6109
Fax: 256-544-7255
E-mail: Alan.Nettles@msfc.nasa.gov

Researchers from NASA and Oak Ridge National Laboratory are evaluating a series of electron beam curable composites for application in reusable launch vehicle airframe and propulsion systems. Objectives are to develop electron beam curable composites that are useful at cryogenic to elevated temperatures (-217 °C to 200 °C), validate key mechanical properties of these composites, and demonstrate cost-saving fabrication methods at the subcomponent level. Electron beam curing of polymer matrix composites is an enabling capability for production of aerospace structures in a non-autoclave process. Payoffs of this technology will be fabrication of composite structures at room temperature, reduced tooling cost and cure time, and improvements in component durability.

This presentation covers the results of material property evaluations for electron beam-cured composites made with either unidirectional tape or woven fabric architectures. Resin systems have been evaluated for performance in ambient, cryogenic, and elevated temperature conditions. Results for electron beam composites and similar composites cured in conventional processes are reviewed for comparison. Fabrication demonstrations were also performed for electron beam-cured composite airframe and propulsion piping subcomponents. These parts have been built to validate manufacturing methods with electron beam composite materials, to evaluate electron beam curing processing parameters, and to demonstrate lightweight, low-cost tooling options.

Manufacture of Porous Ceramic Materials by Combustion Synthesis

L.A. WHELAN ROBINSON, H.C. Yi, and J.Y. Guigné

Guigné International Ltd.
685 St. Thomas Line
Paradise, NF, Canada A1L 1C1
Phone: 709-895-3819
Fax: 709-895-3822
E-mail: guigne@guigne.nf.ca

Porous ceramic materials are suitable for applications in corrosive environment as filters, catalyst supports, pre-forms for composite materials, and thermal insulation materials. A series of porous ceramic materials has been produced using the combustion synthesis technique. These porous materials have a ceramic matrix, such as Al_2O_3, MgO, Al_2O_3-MgO, TiC-Al_2O_3, or Al_2O_3-TiB_2. The combustion behaviors of these ceramic matrix combustion reactions have been characterized fully. The combustion wave velocity ranged from 1 to 5 mm/s, and the combustion temperatures were between 1,500 and 2,000 °C, depending on the chemistries.

All materials exhibited a large degree of linear expansion (100 to 200%) during the combustion reactions. Typical porosity of these materials was greater than 70 % for apparent porosity (open and interconnected pores) and greater than 80% for overall porosity. To control the porosity, several techniques were employed, including adding diluent to the combustion reactions. In addition, porosity control was also achieved by physically confining the sample and through heat treatment. As a result, porosity of these materials can be made to vary over a large range (42 to 83% apparent porosity) and in a controlled manner.

Techniques have been developed to produce materials exhibiting relatively uniform distribution of porosity. As a result, both the compressive strength and modulus of these materials were significantly improved.

The Composites Affordability Initiative

JOHN MISTRETTA

Materials & Manufacturing Directorate
Air Force Research Laboratory
2977 P Street, Room 121
Wright-Patterson Air Force Base, OH 45433-7739 USA
Phone: 937-904-4597
E-mail: john.mistretta@wpafb.af.mil

The Composites Affordability Initiative (CAI) is a multi-service and aerospace industry collaborative effort. This long-range initiative has the goal of developing the technologies and tools necessary to reduce the acquisition cost of composite structures by an order of magnitude. The current phase of CAI includes Joint Strike Fighter-related transition programs at Boeing and Lockheed Martin, plus a cooperative pervasive technology program. This is the second phase of a four-phase effort.

To provide sufficient depth, all relevant areas including design, fabrication, assembly, analysis, quality, and cost models, must be advanced. In the past year, several large producibility articles have been developed to focus the fabrication and assembly technology development process under the pervasive technology program. In addition, cost, analysis, and quality tools have been developed and enhanced.

Aluminum Investment Cast Spacecraft and Aerospace Structures

JOHN BOWKETT

Nu-Cast, Inc.
29 Grenier Field Road
Londonderry, NH 03053 USA
Phone: 603-432-1600
Fax: 603-432-0724
E-mail: nci@grolen.com

The mandate for "better, faster, cheaper" has had a profound effect on aerospace projects. Project personnel, budgets, and development time have been compressed. Coupled with this mandate has been the threat to cancel projects that exceed their budgets. Projects perceived to be grandiose or padding their cost estimates are eliminated or not even considered for selection, regardless of their technical or scientific merit. There is no single solution for this situation. To work effectively in this environment requires an end-to-end approach that reduces project engineering, analysis, drafting, checking, manufacturing, testing, and integration. This approach, above all, must include the desire to depart from standard aerospace engineering practices.

Engineers at Goddard Space Flight Center addressed this changing environment with investment casting technology. Previously, casting had been used for electronic enclosures and some secondary structures; it required production rates of 100 units before being considered. Expanding the technology to primary load path spacecraft structures had been perceived to be costly and of marginal benefit. NASA engineers designed and successfully flew a low-risk investment cast spacecraft and then progressed to a larger, complex monolithic spacecraft for Pegasus-class expendable launch vehicles and primary load path payload structures for the Space Shuttle.

Significant and surprising cost savings have been realized end to end on projects employing this technology. The presentation will showcase advanced applications with aluminum investment casting, the evolutionary approach taken, cost savings realized, technical and political complications encountered, lessons learned, and future work.

Vacuum Plasma Spray of CuCrNb Alloy for Low-Cost, Long-Life Combustion Chambers

FRANK ZIMMERMAN

Marshall Space Flight Center/ED33
Huntsville, AL 35812 USA
Phone: 256-544-4958
Fax: 256-544-0212
E-mail: Frank.R.Zimmerman@msfc.nasa.gov

The copper-8 atomic percent chromium-4 atomic percent niobium (CuCrNb) alloy was developed by Glenn Research Center as an improved alloy for combustion chamber liners. In comparison to NARloy-Z, the baseline alloy for such liners, as those in the Space Shuttle Main Engine, CuCrNb demonstrates mechanical and thermophysical properties equivalent to NARloy-Z, but at temperatures 100 °C to 150 °C (180 °F to 270 °F) higher. Anticipated materials-related benefits include decreasing the thrust cell liner weight 5 to 20%, increasing the service life at least twofold over current combustion chamber design, and increasing the safety margins available to designers. By adding an oxidation and thermal barrier coating to the liner, the combustion chamber can operate at even higher temperatures.

For all these benefits, however, this alloy cannot be formed using conventional casting and forging methods because of the levels of chromium and niobium, which exceed their solubility limit in copper. Until recently, the only forming process that maintained the required microstructure of CrNb intermetallics was powder metallurgy formation of a billet from powder stock, followed by extrusion. This severely limits its usefulness in structural applications, particularly in the complex shapes required for combustion chamber liners. Vacuum plasma spray (VPS) has been demonstrated as a method to form structural articles, including small combustion chambers, from the CuCrNb alloy. In addition, an oxidation and thermal barrier layer can be formed integrally on the hot wall of the liner that improves performance and extends service life.

This paper discusses the metallurgy and thermomechanical properties of VPS-formed CuCrNb versus the baseline powder metallurgy process and the manufacturing of small combustion chamber liners at Marshall Space Flight Center using the VPS process. The advanced propulsion initiative benefits of using VPS to fabricate combustion chamber liners while maintaining the superior CuCrNb properties are also presented.

Dynamic Oxidation of a Plasma-Sprayed Cu-Cr Coating

K.T. CHIANG

The Boeing Company
6633 Canoga Avenue
Canoga Park CA 91309-7922 USA
Phone: 818-586-1211
Fax: 818-586-0575
E-mail: kuang-tsan.k.chiang@boeing.com

The dynamic oxidation of chromium (Cr), copper (Cu), and a plasma-sprayed Cu-30 vol.% Cr coating was investigated in an electric arc-heated wind tunnel. The wind tunnel generated high-velocity, fully dissociated air containing atomic oxygen. The metal surface temperature was maintained at 650 °C for up to 1 hour. The high-velocity atomic-oxygen enhanced oxidative evaporation of Cr metal resulted in rapid metal weight loss. The high-temperature atomic oxygen caused rapid oxide formation on Cu. The scale cracked and spalled severely during cooling to room temperature. For the plasma-sprayed Cu-Cr coating, the oxidation mechanism involved four steps. First, oxidative evaporation of the Cr element resulted in a Cu-enriched surface with increased nucleation sites. Second, rapid whisker formation resulted in a mushroom-like Cu-oxide (CuO) scale morphology. Scale formation involved a combination of surface diffusion, short-circuit diffusion, lattice diffusion, and evaporation. Third, inward migration of oxygen atoms formed a mixed oxide of CuO and $CuCrO_2$. Fourth, a continuous Cr_2O_3 layer formed beneath the external Cu-Cr mixed oxides. The scale morphology and oxidation mechanisms will be compared with those of static laboratory furnace oxidation.

Manufacturing Challenges Implementing Material Changes for Super Lightweight Tank: A Welding Process Perspective

CHIP JONES

Marshall Space Flight Center/ED33
Huntsville, AL 35812 USA
Phone: 256-544-2701
Fax: 256-544-0212
E-mail: Clyde.S.Jones@msfc.nasa.gov

Kirby G. Lawless
Marshall Space Flight Center/ED33
Huntsville, AL 35812 USA
Phone: 256-544-2821
Fax: 256-544-0212
E-mail: Kirby.G.Lawless@msfc.nasa.gov

Aluminum alloy 2195 is a relatively new material originally formulated and patented by Lockheed Martin and Reynolds Metals as a weldable high-strength, low-density aluminum-lithium alloy for cryotank applications. Often mentioned in the same category as composite materials because of its unique strengthening mechanism and anisotropic behavior, implementation of 2195 on the Shuttle's External Tank has been one of NASA's biggest challenges and successes of the last decade. With seven Super Lightweight Tanks flown successfully to date, this success is a credit to the dedication of both the NASA and Lockheed Martin technical communities to overcome many manufacturing challenges. These successes, coupled with planned process improvements, position this alloy as a leading candidate for future generation croytankage. This presentation provides an overview of the challenges specific to the welding processes.

Cryotank Technology Program (CTTP)

TIM VAUGHN

Marshall Space Flight Center/ED35
Huntsville, AL 35812 USA
Phone: 256-544-2607
Fax: 256-544-5786
E-mail: Timothy.P.Vaughn@msfc.nasa.gov

The Cryogenic Tank Technology Program (CTTP) program has been a cooperative effort between Langley Research Center, Marshall Space Flight Center, NASA Headquarters, and industry (Lockheed Martin Aeronautics, Lockheed Martin Manned Space Systems, Wyman Gordon, and Ladish). The scope of the CTTP is to develop state-of-the-art, flight-size, flight-quality, low-cost hardware and to use this hardware to design, fabricate, and test an all aluminum-lithium, all near-net-shape component, 14-foot diameter cryogenic tank with a unique low-profile bulkhead design. The logical conclusion to the CTTP is to validate these various technologies to a Technology Readiness Level (TRL) of 6 through the proposed structural test program.

The CTTP supports the advancement of key enabling technologies required for aluminum-lithium cryogenic tanks. The technologies are focused toward innovative and low-cost manufacturing processes such as near-net-shape technologies: one piece spun-formed domes and extruded barrel panels, and one piece roll-forged ring frames. Other innovative technologies include the friction stir weld process and weight-efficient low-profile bulkhead designs. All of these technologies are of primary importance for NASA's mission plan for reusable and expendable launch vehicles. This program fills the niche for an all-2195 aluminum-lithium alloy cryogenic tank, which is not covered by existing NASA technology work.

Quantitative Hydrocarbon Surface Analysis

VONNIE M. DOUGLAS

The Boeing Company, Rocketdyne
6633 Canoga Avenue
Canoga Park, CA 91309-7922 USA
Phone: 818-586-1476
E-mail: vonnie.m.douglas@boeing.com

The elimination of ozone depleting substances, such as carbon tetrachloride, has resulted in the use of new analytical techniques for cleanliness verification and contamination sampling. The last remaining application at Rocketdyne that required a replacement technique was the quantitative analysis of hydrocarbons by infrared spectrometry. This application, which previously used carbon tetrachloride, was modified successfully using the SOC-400, a compact portable Fourier Transform Infrared manufactured by Surface Optics Corporation. This instrument can measure quantitatively and identify hydrocarbons from solvent flush of hardware as well as directly analyze the surface of metallic components without the use of ozone depleting chemicals. Several sampling accessories are used to perform analysis for various applications.

Ellipsometric Verification and Evaluation of Clean Surfaces

WAYNE THOMPSON

Center for Automation and Robotics
The University of Alabama in Huntsville
Huntsville, AL 35899 USA
Phone : 256-890-6281 or 256-544-2636
Fax: 256-890-6970
E-mail: thompsg@email.uah.edu

As precision cleaning techniques become more critical to the aerospace industry, effective methods of verifying and evaluating those techniques become more important. Precision cleaning can often mean contamination thickness on the order of molecular diameters; therefore, inspection instrumentation must be extremely precise. Ellipsometers provide the measurement capability necessary to determine the contamination of 'clean' surfaces to within a few molecular diameters.

The presentation will describe how ellipsometry is used at Marshall Space Flight Center to evaluate the quality of common solvent-wipe cleaning methods and to verify the cleanliness of critical-process witness surfaces.

Improved Detection Technique for Solvent Rinse Cleanliness Verification

STEVEN D. HORNUNG

Allied Signal Technical Services Corporation
White Sands Test Facility
P.O. Box 20, MS 201LD
Las Cruces, NM 88004 USA
Phone: 505-524-5647
E-mail: steven.d.hornung1@wstf.nasa.gov

Harold D. Beeson
Johnson Space Center
White Sands Test Facility
P.O. Box, MS RF
Las Cruces, NM 88004 USA
Phone: 505-524-5542
Fax: 505-524-5260
E-mail: harold.d.beeson1@wstf.nasa.gov

The White Sands Test Facility (WSTF) has an ongoing effort to reduce or eliminate use of cleaning solvents such as CFC-113 and its replacements. These solvents are used in the final cleaning and cleanliness verification process for flight and ground support hardware, especially for oxygen systems where organic contaminants can pose an ignition hazard.

An improved cleanliness verification process has been developed at WSTF that reduces the amount of solvent sampled and the time required for nonvolatile residue (NVR) detection and allows resampling of the solvent rinse.

For cleanliness verification in accepted sampling procedures, the equivalent of 0.1 m^2 (1 ft^2) surface area of a part or parts is rinsed with the solvent, and the final 100 mL of the rinse is captured. The amount of NVR in the solvent is determined by weight after evaporation of the solvent. The improved process of analyzing this rinse requires evaporation of less than 2 mL of the solvent to make the cleanliness verification. Small amounts of the solvent are evaporated in a clean stainless-steel cup, and the cleanliness of the stainless-steel cup is measured using a commercially available surface quality monitor. This process reduces the time required from 45 min to 5 min, results in solvent savings, and allows resampling of the solvent rinse.

Testing with known contaminants in solution, such as hydraulic fluid, fluorinated lubricants, and cutting and lubricating oils, was performed to establish a correlation between the amount in solution and the process response. The results using this new surface quality monitor-based cleanliness verification technique will be compared to the accepted NVR sampling procedures.

Criteria for NVR Solvent Replacement

KENNETH LUEY, Dianne J. Coleman, Joseph C. Uht, and Graham S. Arnold

The Aerospace Corporation
2350 E. El Segundo Blvd
El Segundo, CA 90245 USA
Phone: 310-336-5499
Fax: 310-336-7055
E-mail: kenneth.t.luey@aero.org

Control of contamination during processing and integration of spacecraft and launch vehicles is needed to ensure mission performance and predicted life. Molecular contamination, measured as nonvolatile residue (NVR), is limited and controlled through proper materials selection, preprocessing, and control of procedures and facility environments. Measurement of NVR accretion during ground processing of space hardware relies on the use of toxic and ozone depleting solvents (methylene chloride and 1,1,1 trichloroethane).

This presentation describes the development of a 'scoring system' for evaluating the effectiveness, toxicity, and environmental impact of organic solvents. The figures of merit include the Hanson parameter, threshold limit value, inhalation hazard value, immediate danger to life and health, and flash point. The scoring system is used to identify and test a substitute for methylene chloride.

Critical Surface Cleaning and Verification Alternatives

DONALD M. MELTON

Lockheed Martin Michoud Space Systems
P.O. Box 29304
Michoud Assembly Facility
New Orleans, LA 70189 USA
Phone: 504-257-1782
E-mail: Donald.M.Melton@maf.nasa.gov

Reduction efforts over the past few years have successfully reduced target compounds such as trichloroethylene (99%), Freon® Precision Cleaning Agent (PCA) (96%), and Freon® TMC (100%). With these accomplishments in place, efforts are continuing to identify and test effective, user-friendly options. HCFC 225g and HFE 7100 were assessed as liquid oxygen cleaning and verification options for HCFC 225 and as a clean handwipe option for Freon® PCA.

The Effects of Cryogenic Treatment on the Mechanical Properties of an Al-Li Alloy 2195

PO CHEN and Robert Bond

IITRI
Marshal Space Flight Center/ Bldg. 4612 (Chen), Bldg. 4625 (Bond)
Huntsville, AL 35812 USA
Phone: 256-544-4171 (Chen)
256-544-8277 (Bond)
Fax: 256-544-6755 (Chen)
256-544-6742 (Bond)
E-mail: PoShou.Chen@msfc.nasa.gov
Robert.Bond@msfc.nasa.gov

Tina Malone
Marshall Space Flight Center/ED33
Huntsville, AL 35812 USA
Phone: 256-544-2593
Fax: 256-544-5877
E-mail: Tina.W.Malone@msfc.nasa.gov

Pablo Torres
Marshall Space Flight Center/ED33
Huntsville, AL 35812 USA
Phone: 256-544-2616
Fax: 256-544-5877
E-mail: Pablo.D.Torres@msfc.nasa.gov

The effects of cryogenic temperatures on metals were first analyzed by NASA engineers after spacecraft returned from the cold vacuum of space. They noticed that many metal parts in the spacecraft came back stronger than they were before flight. Since then, reports have appeared in the United States and Europe of substantial benefits that can be realized by treating steel tools at a low temperature, usually those near that of liquid nitrogen [-320 °F (-196 °C)]. The benefits of cryogenic treatment include improvements on mechanical properties, wear resistance, dimensional stability, and tool life. More recently within the United States, the observed improvements have been expanded to include copper, some high-temperature alloys, carbides, and plastics.

At Marshall Space Flight Center, the potential benefits of cryogenic tempering on Al-Li alloys are being studied. This type of processing has been proven in industry to provide significant benefits in strength and dimensional stability for other aluminum alloys, such as Al6061. The cryogenic treatment for Al-Li alloys includes: (1) slowly cooling (without thermal shock) the already heat-treated material to approximately -320 °F (-196 °C), (2) holding at low temperature for a day or two, (3) reheating without thermal shock to room temperature. The effects of cryogenic treatment on strength, toughness, fatigue life, and residual stress will be studied. Variations in microstructure as a result of cryogenic treatment will also be reported in the paper.

Toughness of Ultra High Strength AF1410 Type Steels

LUANA E. IORIO

Department of Materials Science and Engineering
Carnegie Mellon University
Pittsburgh, PA 15213 USA
Phone: 412-268-2699
Fax: 412-268-7596
E-mail: li25@andrew.cmu.edu

Warren M. Garrison, Jr.
Department of Materials Science and Engineering
Carnegie Mellon University
Pittsburgh, PA 15213 USA
Phone: 412-268-3593
Fax: 412-268-7596
E-mail: wmg@andrew.cmu.edu

This study presents a discussion of AF1410-type steels and their related toughness. The ultra high strength of secondary hardening steel AF1410 combines high strength with excellent fracture toughness properties. AF1410 has a nominal composition of 0.16C/14 Co/10 Ni/ 2Cr/ 1Mo. One approach to increasing the strength of this material is to increase the carbon level; however as the carbon level is increased, the toughness decreases significantly with only moderate strength gains.

This work has focused on the influence of a number of factors on AF1410 toughness. Carbon levels have been varied from 0.16 to 0.25 wt% resulting in yield strengths that vary from 1,530 MPa to 1,690 MPa. The effect of sulfide inclusion type and distribution has also been studied. It has been found that small titanium additions cause the sulfur to be gettered into titanium carbosulfide particles. These particles are more resistant to void nucleation than the chromium sulfide, manganese sulfide, or rare-earth oxysulfides typically found in these types of steel. AF1410 with a small titanium addition can achieve a Charpy impact energy of 205 J and a fracture toughness value of 347 MPa.m1/2, compared to 70 J and 158 MPa.m1/2 when the sulfides are MnS.

The support of the National Science Foundation under DMR-9712620 is gratefully acknowledged.

Segregation Behavior of Sulfur and Other Impurities onto the Free Surfaces in ED-Ni Deposits

BINAYAK PANDA

IITRI
Marshall Space Flight Center/Bldg. 4612
Huntsville, AL 35812 USA
Phone: 256-544-6349
Fax: 256-544-9190
E-mail: Binayak.Panda@msfc.nasa.gov

Gregory Jerman
Marshall Space Flight Center/ED33
Huntsville, AL 35812 USA
Phone: 256-544-5346
Fax: 256-544-5877
E-mail: Gregory.A.Jerman@msfc.nasa.gov

Electro-deposited nickel (ED-Ni) has its unique application in the main combustion chamber in rocket engines. Since the material is produced as an electrolytic deposition, impurities that are associated with the electrolyte co-deposit on the built-up surface with the Ni atoms. Presence of some of these impurities, such as sulfur, bismuth, and tellurium, are known to have deleterious effects during subsequent processing of the deposited metal, which involves increased temperature and pressure. To cause deleterious effects such as cracking and grain boundary separation, these elements, which may be present in small quantities (parts per million), segregate onto the grain boundaries in proportions much larger than their levels in the matrix.

This paper presents data of surface analysis using Electron Spectroscopy for Chemical Analysis, bulk analysis using microprobe, and combustion analysis on several samples of ED-Ni. Impurity elements, their segregation propensity, and the conditions under which they segregate have been elaborated. Findings have been compared with the existing literature of segregation behavior.

Statistical Analysis of Al-Li 2195 Strength and Toughness Data

LYNN NEERGAARD

IITRI
Marshall Space Flight Center, Bldg. 4708
Huntsville, AL 35812 USA
Phone: 256-544-5181
Fax: 256-544-7473
E-mail: Lynn.Neergaard@msfc.nasa.gov

Tina Malone
Marshall Space Flight Center/ED33
Huntsville, AL 35812 USA
Phone: 256-544-2593
Fax: 256-544-5877
E-mail: Tina.W.Malone@msfc.nasa.gov

Since flight verification of the Super Lightweight External Tank (SLWT), 100% lot acceptance testing has been applied to each aluminum-lithium dome and barrel sections fabricated into these tanks. These data have been archived and organized by Lockheed Martin on behalf of Marshall Space Flight Center.

This presentation analyzes statistical trends in strength and toughness data. Data have been gathered since the beginning of the material modification. Only recently has Al-Li 2195 been made in production quantities, with composition and process optimized for the external tank. The statistical analysis to be presented has focused on the most recent production data, rather than the earlier development data.

Residual Stress Prediction in Machined Workpiece Surface

PAUL BAYER

Third Wave Systems, Inc.
7301 Ohms Lane
Minneapolis, MN 55379 USA
Phone: 952-832-5515
Fax: 952-844-0202
E-mail: paulb@thirdwavesys.com

Troy Marusich
Third Wave Systems, Inc.
7301 Ohms Lane
Minneapolis, MN 55379 USA
Phone: 952-832-5515
Fax: 952-844-0202
E-mail: troym@thirdwavesys.com

New tooling and high-speed machining technologies have raised performance expectations for controlling workpiece quality, integrity, stresses, and fatigue properties that are difficult and expensive to determine, measure, or test. New modeling technologies now exist that can predict the effects of cutting on the quality of the remaining material. Parameters considered are the workpiece material properties, tooling geometries, cutting operations, and pre-existing stress conditions. Validated analysis includes thermal and mechanical deformation, surface layer effects, and stresses induced from the cutting process itself. Aerospace industry examples include part deformation and fatigue problems economically resolved with the use of residual stress modeling techniques.

Easily Processable High-Temperature and Flame-Resistant Phthalonitrile Composites for Aerospace Applications

TEDDY M. KELLER

Chemistry Division, Code 6127
Naval Research Laboratory
Washington, DC 20375-5320 USA
Phone: 202-767-3095
Fax: 202-767-8594
E-mail: keller1@ccf.nrl.navy.mil

Harry N. Jones
Materials Division, Code 6325
Naval Research Laboratory
Washington, DC 20375-5320 USA
Phone: 202-767-1278
E-mail: jones@anvil.nrl.navy.mil

Phthalonitrile-based polymers under development at the Naval Research Laboratory (NRL) offer promise of bridging the gap between currently used high-temperature polymers and ceramics/ metals. Replacement of metal by fiber-reinforced phthalonitrile composites would effect substantial weight, cost, and energy savings and improve performance. The phthalonitrile-based prepolymer exhibits unique properties not seen in other commercially available high-performance materials being used for composite fabrication, such as indefinite ambient stability of prepregs and ease of processability into composite components by regular prepreg consolidation, resin transfer molding, resin injection molding, or filament winding from the melt of the prepolymer. The phthalonitrile composite exhibits outstanding water resistance (<1% by weight at equilibrium). The phthalonitrile composites show promise for the fabrication of primary structural components and for turbine engine applications up to 375 °C because of the superior thermo-oxidative stability and the absence of a glass transition temperature (T_g). Moreover, the phthalonitrile-based composites retain structural integrity to 540 °C (1,000 °F) in air for short exposures with rapid decomposition occurring at 590 °C (1,100 °F) and show superior flammability properties. The relative concentration of toxic gas, *e.g.,* carbon monoxide, as measured by cone calorimetry, is extremely low when compared to other high-performance composites at a heat source of 100 kW/m^2. Our current research activities are concerned with the optimization of processing parameters and expansion of the database.

Presently, the phthalonitrile composite technology is being evaluated by industry for aerospace (turbine engine and missile) and marine (ship and submarine) applications because of the ease of processability and unique physical properties at elevated temperatures. The composite technology has been licensed by GKN Westland Aerospace, Inc. Several other companies are currently negotiating licensing agreements with the Navy.

Real-Time Video Recording of Extremely High-Temperature Processes

THAD HOFFMAN

Control Vision, Inc.
P.O. Box 51505
Idaho Falls, ID 83405 USA
Phone: 208-523-5506
Fax: 208-523-5520
E-mail: vision@controlvisioninc.com

Extremely high-temperature processes (greater than 750 °C) are characterized visually by their high luminosity related to incandescence. When one wishes to view the surface of material at such elevated temperatures, the fact that the surface itself is giving off light causes problems with the ability to create a high-contrast image. Even worse, when one attempts to use an ordinary video or photographic camera, the need to attenuate the prevailing light from the material surface makes it nearly impossible to achieve proper exposure throughout the image.

This presentation will describe a robust video technique that has been developed to ignore incandescence and to produce high-quality, highly contrasted, real-time video imagery using reflected illumination. Reflected illumination is the means by which we normally observe the details of our world. This video technique has been used to view surface details of processes at a few hundred degrees Celsius, such as resistively or combustion-heated materials, or processes at several thousand degrees Kelvin, such as particles entrained within a thermal plasma jet.

Vapor-Grown Carbon Fiber/Phenolic Matrix Composites for Rocket Nozzles and Heat Shields

R.D. PATTON

Mechanical Engineering Department
P.O. Box ME
Mississippi State University
Mississippi State, MS 39762 USA
Phone: 662-325-7311
Fax: 662-325-7223
E-mail: patton@me.msstate.edu

C.U. Pittman, Jr.
Chemistry Department
P.O. Box 9573
Mississippi State University
Mississippi State, MS 39762 USA
Phone: 662-325-7616
Fax: 662-325-7611
E-mail: cpittman@ra.msstate.edu

L. Wang
Chemical Engineering Department
P.O. Box CH
Mississippi State University
Mississippi State, MS 39762 USA
Phone: 662-325-3584
E-mail: Lw2@ra.msstate.edu

J.R. Hill
3536 Idaho Road
Charleston Air Force Base, SC 29404 USA

A. Day
Thiokol Propulsion
Marshall Space Flight Center/Bldg. 4712
P.O. Box 9033
Huntsville, AL 35812 USA
Phone: 256-544-4128

The ablation, mechanical, and thermal properties of vapor-grown carbon fiber (VGCF)/ phenolic resin composites were evaluated to determine the potential of using this material in solid rocket motor nozzles and heat shields. Composite specimens with varying VGCF loading (30% to 50% weight), including one sample also containing ex-rayon carbon fiber plies, were prepared and exposed to a plasma torch for 20 seconds with a heat flux of 16.5 MW/m^2 at approximately 1,650 °C. Low erosion rates and little char formation were observed, confirming that these materials have promise as rocket motor nozzle materials. When fiber loadings increased, mechanical properties and ablative properties improved. The VGCF composites had low thermal conductivities (approximately 0.56 W/m-°C), indicating they were good insulating materials. If a 65% fiber loading in VGCF composite can be achieved, ablative properties are projected to be comparable to or better than the composite material currently used on the Space Shuttle Reusable Solid Rocket Motor.

The ablation of the composite specimens proceeded with very thin flakes falling uniformly from the specimen. Despite the low thermal conductivity, no hot spot was observed on the specimen surface where the plasma torch impinged. The specimens appeared to conduct heat evenly across the surface but not to the interior. The extremely small size of the fibers plays a role in these properties. During ablation, a thin layer of carbon/carbon matrix (with higher thermal conductivity) forms on the surface, spreading heat across the surface by resin pyrolysis to a graphite-like coat; however, heat penetration into the interior is low. These composites are made by forming and molding a paste. Potentially, this process offers significant cost savings over the current practices of fiber placement and filament winding.

Ambient Air Monitoring and Respirable Particulate Matter (PM_{10}) and Total Suspended Particulate (TSP) during the RD-180 Rocket Engine Tests at the NASA Marshall Space Flight Center

JOHN HUGHES

Science Services Laboratory
John C. Stennis Space Center, MS 39529 USA
Phone: 228-688-3166
Fax: 228-688-1039
E-mail: John.Hughes@ssc.nasa.gov

Kathy Lehr
Science Services Laboratory
John C. Stennis Space Center, MS 39529 USA
Phone: 228-688-3983
Fax: 228-688-1039
E-mail: Kathy.Lehr@ssc.nasa.gov

The Science Services Laboratory, located at Stennis Space Center and operated by GB Tech, was tasked by Marshall Space Flight Center's Environmental Office to assess the environmental impact of air particulate matter as a result of RD-180 engine testing. The method for monitoring ambient air includes measuring particles ≤10 μ (PM_{10}), particles with diameters ≤2.5 μ ($PM_{2.5}$) and Total Suspended Particles (TSP) that have a diameter size of 25 to 50 μ. This particulate matter represents small dust-like particles of soot, which are sufficiently small to disperse like a permanent gas. Because of their small size, these particulates can be inhaled. The airborne concentrations are regulated and set by the Environmental Protection Agency to prevent adverse effects associated with the inhalation of high levels of particulates.

Dedicated samplers were used to collect the correct particle size from the ambient air. The samplers also maintained a controlled flow rate to determine the volume of air sampled. Particles were collected on micro-quartz or glass fiber filters that were equilibrated and weighed before (tare) and after (gross) sampling to determine the weight (net mass) gain of the sample. The concentration of the particles captured from the air was then computed as the net mass collected by the volume of air sampled. Location of the samplers was based on plume modeling diagnostics and real-time atmospheric conditions of wind speed and direction. This method provides a measurement of the mass concentration of airborne particulate matter for the determination of compliance with National Ambient Air Quality Standards.

Gas Emission Measurements from the RD-180 Rocket Engine Tests at the NASA Marshall Space Flight Center

H. RICHARD ROSS

Test & Engineering Directorate, Science Laboratory
Lockheed Martin / GB Tech
Stennis Space Center, MS 39529 USA
Phone: 228-688-2353
Fax: 228-688-3975
E-mail: Harold.Ross@ssc.nasa.gov

Under a Space Act Agreement with Lockheed Martin Astronautics of Denver, Marshall Space Flight Center provided a series of test firings for the Atlas IIIa propulsion systems configured with a Russian-built RD-180 rocket engine. The tests were designed to measure the performance of the Atlas propulsion system, which includes avionics and propellant subsystems, and to determine how these components interact with the RD-180 engine.

The Russian engines are powered with oxygen/RP-1 (kerosene) propellants that feature a liquid oxygen lead start and a staged combustion cycle, providing 860,400 pounds of thrust at sea level. The engines are approximately twice as powerful for their weight as current U.S. models and have completed extensive testing. This was the first Russian-built rocket engine to be tested at a U.S. Government facility. The use of the RD-180 will also mark the first time a Russian rocket motor has powered a U.S. spacecraft to orbit.

The Science Laboratory at the NASA Stennis Space Center was tasked by the Environmental Office at MSFC to collect plume samples and to measure the gaseous components from the static firings of the Atlas III/RD-180 test article. This paper describes the Fourier Transform Infrared methods and other techniques that were used to measure the exhaust emissions. These data will be used to validate plume prediction codes and to assess environmental air quality issues.

Development of Lead-Free Energy Absorber for Space Shuttle Blast Container

DONALD BALLES, Thomas Ingram, Howard Novak, and Albert Schricker

United Space Alliance, Inc.
Attn: H.L. Novak, M/S USK-864
8550 Astronaut Boulevard
Cape Canaveral, FL 32920-4304 USA
Phone: 321-867-7052
E-mail: novakh@usasrb.ksc.nasa.gov

The Space Shuttle Vehicle (SSV) is connected to the Mobile Launch Platform (MLP) by four aft skirt hold-down studs on each Solid Rocket Booster (SRB). Before liftoff, the frangible nuts inside the aft skirt Blast Containers (BCs) are severed into two nut halves by two pyrotechnic booster cartridges. This action releases the SSV and allows the hold-down studs to eject through the aft skirt bore and then down into the MLP.

United Space Alliance's SRB Element was tasked to upgrade the BC for two reasons: (1) to eliminate lead for environmental concerns and (2) to reduce the chance of nut recontact with the hold-down stud. Nut recontact with the stud has been identified as a likely contributor to stud hangups. This upgrade will replace the lead liner with a unique open-cell aluminum foam material that has commercial and military uses. The aluminum foam, used as an energy absorber, is a proven design in many aerospace/defense applications and has been declassified recently. Additional benefits of using the open-cell, energy-absorbent aluminum foam in place of the solid lead liner are: (a) lead handling/exposure and possible contamination, along with hazardous waste disposal, will be eliminated; (b) approximately 200 pounds of weight savings will be contributed to each Space Shuttle flight by using aluminum foam instead of lead; (c) the new aluminum liner is designed to catch all shrapnel from frangible nuts, thus virtually eliminating the chance of foreign object debris exiting the hold-down post and causing potential damage to the vehicle; and (d) using the lighter aluminum liner allows for easier assembly and disassembly of blast container elements and for improvements in safety, operator handling, and efficiency of operations.

Six BC firing tests were required to determine if the new liner material would decrease the chance of stud hangups and enhance the ability of the BC to retain blast debris. Test firing performed at the Kennedy Space Center (KSC) Launch Equipment Test Facility (LEFT) simulated the SRB hold-down post, with actual BC hardware and pyrotechnics assembled. Initial testing was performed using a frangible nut in a static drop test over lead and aluminum foam sheet materials. The aluminum foam showed a dramatic improvement of energy absorption over the lead liner material. Proof of Principle testing, completed on schedule at the KSC LEFT, showed the excellent performance characteristics of the lightweight, open-cell aluminum foam material.

Polymer Matrix Composites (PMCs) Cryopipe for Rocket Engine Lines and Ducts

DAVID BETTINGER

The Technology Partnership
8030 Coventry
Grosse Ile, MI 48138-1119 USA
Phone: 734-675-8295
Fax: 734-675-8296
E-mail: techpart@home.com

Alloy rocket engine ducts and lines have been targeted for conversion to lighter, polymer composites. The concern with polymer composites is assured performance for multiple reuse. The need is for stress control and polymer protection from LOX and LH_2. A suite of seven polymer composite technologies is presented that make the component fabrication, assembly, and performance of polymer cryopipe practical and economical. Flanges are eliminated and expensive expansion alloy bellows are replaced by more efficient and lightweight components.

These technologies use stress design to configure superior performance composites with existing space-qualified materials. The Air Force Research Laboratory and the Ballistic Missile Defense Organization have funded these developments.

Nanotechnology Concepts at Marshall Space Flight Center – Engineering Directorate

BILIYAR BHAT, Raj Kaul, Sandeep Shah, Gweneth Smithers, and Michael D. Watson

Marshall Space Flight Center/ ED33
Huntsville, Alabama 35812 USA
Phone: 256-544-2596
Fax: 256-544-5877
E-mail: Biliyar.Bhat@msfc.nasa.gov

Nanotechnology is the art and science of building materials and devices at the ultimate level of finesse: atom by atom. Our nation's space program has need for miniaturization of components, minimization of weight, and maximization of performance, and nanotechnology will help us get there. MSFC's Engineering Directorate is committed to developing nanotechnology that will enable MSFC missions in space transportation, space science, and space optics manufacturing. MSFC has a dedicated group of technologists who are currently developing high-payoff nanotechnology concepts. This poster presentation will outline some of the concepts being developed including, nanophase structural materials, carbon nanotube reinforced metal and polymer matrix composites, nanotube temperature sensors, and aerogels. The poster will outline these concepts and discuss associated technical challenges in turning these concepts into real components and systems.

ISO 9000 and the Environment

LEE C. BRAVENER

National Quality Assurance, USA
1984 Johnson Road
Point Roberts, WA 98182 USA
Phone: 360-945-1595
E-mail: nqausapr@pointroberts.net

Stanley Fielding
National Quality Assurance, USA
4 Post Office Square Road
Acton, MS 01720 USA
Phone: 1-800-649-5289
E-mail: sfielding@nqa-usa.com

Deploying an Environmental Management System (EMS) modeled on the ISO 14001 international standard in an aerospace organization can be daunting. Work-force restrictions, schedules, resource conflicts, shrinking budgets, and competition increase the complexity of this challenge. Use of a pre-existing ISO 9000 Quality Management System (QMS) provides a unique opportunity for the aerospace industry to develop an ISO 14001 EMS. A central theme prevalent in both the successful EMS and QMS is that the management systems must be fully integrated into the business infrastructure of the organization. Foreseeably, the implementation of two distinctly separate systems could adversely impact the organization. Functional similarities exist between the EMS and QMS that are mutually supportive. Additionally, the introduction of the next revision of ISO 9000 (ISO9000:2000) will introduce structural and regulatory changes that intentionally mimic ISO 14001.

A pre-existing, properly functioning QMS will provide established avenues of communication and process throughout the organization. The EMS champion would be prudent to access these known avenues of communication and process to infuse new system requirements into the infrastructure of the organization. It would be suggested that modifications to an EMS system be kept to a minimum initially. The EMS champion would be advised to use the established elements of the QMS: Management Review, Record Control, Internal Audit, Corrective Action, Document Control, and other joint systems. The “new” EMS requirements could be structured and developed separately, tested for functional performance, and integrated into the organization using the infrastructure from the established QMS.

The joint QMS/EMS can most certainly prove that the whole is greater than the sum of the parts. Using the established QMS-compliant system is the best approach for the implementation of an equally compliant EMS. Alternatively, the use of the successful EMS would be the best approach for the implementation of the successful QMS as well.

Presence of Magnesium in Aerospace, Then and Now

ROBERT E. BROWN

Magnesium Assistance Group, Inc.
226 Deer Trace
Prattville, AL 36067-3806 USA
Phone: 334-365-9184
Fax: 334-365-9184
E-mail: Magman6@aol.com

Historically, magnesium, the lightest weight structural metal, has been used in aerospace applications. The German military aircraft industry made extensive use of magnesium, as did the rocket industry. The U.S. built an instant magnesium industry for WWII aircraft, including engine castings and wheels. The adhesively applied skins and castings of the B-36 used 20,000 pounds of magnesium. Additionally, large amounts of magnesium were used for the fabrication of B-52s and B-47s. The Titan I, Vanguard, Jupiter, Polaris and Thor-Able Star used magnesium sheet. Vanguard, the first U.S. satellite, was fabricated from sheet magnesium. The Soviet Union also used magnesium in its aerospace program. This paper will explore the rich history of magnesium in the aerospace industry. Additionally, the paper will address the use of magnesium in today's aerospace industry.

Microstructure, Mechanical Properties, Hot-Die Forming, and Joining of 47XD Gamma TiAl Rolled Sheets

G. DAS

Pratt & Whitney
P.O. Box 109600
West Palm Beach, FL 33410-9600 USA
Phone: 561-796-6744
Fax: 561-796-7454
E-mail: dasgopal@pwfl.com

S. Draper, J.D. Whittenberger, and P.A. Bartolotta
Glenn Research Center
2100 Brookpark Road
Cleveland, OH 44135-3191 USA
Phone: 216-433-3257 (Draper); 216-433-3196 (Whittenberger); 216-433-3338 (Bartolotta)
Fax: 216-433-8000
E-mail: Susan.L.Draper@lerc.nasa.gov; John.D.Whittenberger@lerc.nasa.gov; Paul.A.Bartolotta@lerc.nasa.gov

The microstructure and mechanical properties, along with the hot-die forming and joining of Ti-47Al-2Nb-2Mn-0.8 vol% TiB_2 sheets (known as 47XD), produced by a low-cost rolling process, were evaluated. A near-gamma microstructure was obtained in the as-rolled condition. The microstructures of heat-treated sheets ranged from a recrystallized equiaxed near-gamma microstructure at 1,200 to 1,310 °C, to a duplex microstructure at 1,350 °C, to a fully lamellar microstructure at 1,376 °C. Tensile behavior was determined for unidirectionally rolled and cross-rolled sheets for room temperature (RT) to 816 °C. Yield stress decreased gradually with increasing deformation temperature up to 704 °C; above 704 °C, it declined rapidly. Ultimate tensile strength exhibited a gradual decrease up to 537 °C before peaking at 704 °C, followed by a rapid decline at 816 °C. The modulus showed a gradual decrease with temperature, reaching ~72 percent of the RT value at 816 °C. Strain to failure increased slowly from RT to 537 °C; between 537 °C and 704 °C, it exhibited a phenomenal increase, suggesting that the ductile-brittle transition temperature was below 704 °C. Fracture mode changed from transgranular fracture at low temperature, to a mixture of transgranular and intergranular fracture at intermediate temperature, to ductile fracture at 816 °C, coupled with dynamic recrystallization at large strains. Creep rupture response was evaluated between 649 and 816 °C over the stress range of 69 to 276 MPa. Deformation parameters for steady-state creep rate and time-to-rupture were similar: activation energies of ~350 kJ/mol and stress exponents of ~4.5. Hot-die forming of sheets into corrugations was done at elevated temperatures in vacuum. The process parameters to join sheets by diffusion bonding and brazing with TiCuNi 70 filler alloy were optimized for test coupons and successfully used to fabricate large truss-core and honeycomb structures. Nondestructive evaluation methods, *e.g.,* ultrasonic C-scans and thermography along with metallography, were used to characterize bond quality. Microstructural evaluation during heat treatment, identification of phases at the braze/matrix interface, determination of shear strengths of brazed joints, and deformation mechanisms during tensile and creep processes will be discussed.

At Last, Something New!
Cleaning without Chemistry, and Reusing the Waste Water!

JOHN DURKEE

Creative EnterpriZes
105 Anyway, Suite 209
Lake Jackson, TX 77566
Phone: 815-547-5650 x200
Fax: 815-544-2287
E-mail: jdurkee@precisioncleaning.com

The poster describes research performed by Creative EnterpriZes and a client firm to investigate management of industrial soils from their existence on parts to their disposal as a concentrate in water. These soils came from the manufacture of metal parts and include oils used for drawing, forming, cutting, grinding, lubricating, and honing; phosphate-based lubricants used in compression threading; dry lubricants, such as molybdenum disulfide; and other materials whose composition was unknown.

The research produced the following knowledge:

- How these soils could be cleaned from parts using only ultrasonic energy and without use of cleaning chemistry
- How these soils could be made so as to not reinfect the parts in the cleaning bath
- The surprising effects of temperature and cleaning time on surface finish
- How to construct an evaporator for separation of the soils from water
- Specifications about recycle of the distilled and condensed liquid water.

The technology had been used at both high-precision and low-quality levels of cleaning. This knowledge has been implemented in full-scale cleaning machines, which also will be described.

Polymer Matrix Composite (PMC) Analog Processes for Lightweight Aluminum Matrix Composite (AMC) Structures

BRIAN GORDON

Touchstone Research Laboratory
RD1 Box 100B
The Millennium Center
Triadelphia, WV 26059 USA
Phone: 304-547-5800
Fax: 304-547-4069
E-mail: blg@trl.com

Next-generation hypersonic aircraft, reusable launch vehicles, and low-cost spacecraft require new materials to meet decreasing vehicle weights, increasing payload capacity, and dramatically lower operating costs. Materials that have improved specific strength and specific stiffness, especially at cryogenic and elevated temperatures, enable commercial and Government customers to meet these aggressive program goals by supporting development of stronger, lighter, and more thermally stable integrated components. Touchstone's Brazed Aluminum Matrix Composite (AMC) material has nearly twice the specific strength and specific stiffness of structural aluminum alloys and maintains these properties at higher temperatures than current aerospace alloys. When *in situ* brazed from thin tape, the manufacturing of large highly integrated structures is possible with minimal tooling. As such, this material and associated manufacturing process can serve as an enabling technology for many aircraft and spacecraft applications, including engine and thrust structures, feed lines and ducts, propellant tanks, and thermally stable satellite structures. This poster presentation discusses a new material and, more specifically, a new manufacturing system that enables development of high-performance aircraft and spacecraft components.

Further Studies of Materials Compatibility in High-Test Hydrogen Peroxide

RUDY GOSTOWSKI

Department of Chemistry
Austin Peay State University
Box 4547
Clarksville, TN 37044 USA
Phone: 931-648-7624
Fax: 931-648-5996
E-mail: gostowskir@apsu01.apsu.edu

Tom Owens
Marshall Space Flight Center
Huntsville, AL 35812 USA

Assessment of the compatibility of high-test hydrogen peroxide (HTP) with materials, in particular new materials such as composites, is critical to the development of new propulsion systems meeting requirements of reduced cost and environmental impact. While compatibility with HTP has been addressed previously, newer materials were not considered. The focus of this project was to develop a scheme for evaluation of HTP with all materials. In the previous summer, methods were developed for production of HTP on site, and preliminary steps were taken to evaluate materials. Methods investigated this summer have included accelerated aging by heating, coupled with assay of concentration and stabilization loss, observation of reactivity by means of Isothermal Microcalorimetry, and evaluation of changes to the materials by Short Beam Shear testing and by Photoacoustic-Fourier Transform Infrared Spectroscopy. Various metals, polymers, and composites were examined in this study.

X-traktor: A Rookie Robot, Simple, Yet Complex, Impeccably Designed, A Very Innovative Multidisciplinary Engineering Masterpiece

ARTHUR J. HENDERSON, JR.

Marshall Space Flight Center/ED36
Huntsville, AL 35812 USA
Phone: 256-544-2577
Fax: 256-544-5877
E-mail: arthur.henderson@msfc.nasa.gov

FIRST is the acronym of For Inspiration and Recognition of Science and Technology. FIRST is a 501.C.3 non-profit organization whose mission is to generate an interest in science and engineering among today's young adults and youth. This mission is accomplished through a robot competition held annually in the spring of each year. NASA's Marshall Space Flight Center, Education Programs Department, awarded a grant to Lee High School, the sole engineering magnet school in Huntsville, Alabama. MSFC awarded the grant in hopes of fulfilling its goal of giving back invaluable resources to its community and engineers, as well as educating tomorrow's work force in the high-tech area of science and technology.

Marshall engineers, Lee High School students and teachers, and a host of other volunteers and parents officially initiated this robot design process and competitive strategic game plan. The FIRST Robotics Competition is a national engineering contest, which immerses high school students in the exciting world of science and engineering. Teaming with engineers from government agencies, businesses, and universities enables the students to learn about the engineering profession. The students and engineers have 6 weeks to work together to brainstorm, design, procure, construct, and test their robot. The team then competes in a spirited, "no-holds barred" tournament, complete with referees, other FIRST-designed robots, cheerleaders, and time clocks.

The partnerships developed between schools, government agencies, businesses, and universities provide an exchange of resources and talent that build cooperation and expose students to new and rewarding career options. The result is a fun, exciting, and stimulating environment in which all participants discover the important connections between classroom experiences and real-world applications.

This paper will highlight the story, engineering development, and evolutionary design of X-traktor, the rookie robot, a manufacturing marvel and engineering achievement.

Characterization of Ceramic Matrix Composite Combustor Components: Pre and Post Exposure

G. OJARD

United Technologies Research Center
411 Silver Lane M/S 129-24
East Hartford, CT 06108 USA
Phone: 860-610-7013
E-mail: OjardGC@utrc.utc.com

G. Linsey and J. Brennan
United Technologies Research Center
411 Silver Lane
East Hartford, CT 06108 USA

R. Naik, R. Cairo, R. Stephan, and J. Hornick
Pratt & Whitney
United Technologies Corporation
400 Main Street
East Hartford, CT 06108 USA

D. Brewer
Glenn Research Center/MS 49 - 7
21000 Brookpark Road
Cleveland, OH 44135 USA
Phone: 216-433-3304
Fax: 216-433-8000
E-mail: David.N.Brewer@lerc.nasa.gov

The pursuit of lower emissions and higher performance from gas turbine engines requires the development of innovative concepts and the use of advanced materials for key engine components. One key engine component is the combustor, where innovative design and material improvements have the potential to lower emissions. Efforts to develop a High Speed Civil Transport with low emissions were focused on the evaluation of combustor concepts with liners fabricated from a ceramic matrix composite of silicon carbide fibers in a silicon carbide matrix (SiC/SiC). The evaluation of SiC/SiC composites progressed from simple coupons (to establish a first-order database and identify operant failure mechanisms and damage accumulation processes), to feature-based subelements (to assess fabricability and *in situ* material response), to actual components (to assess structural integrity, dimensional, and compositional fidelity) tested under simulated engine conditions.

As in the case of all evolutionary material and process work, a key element to resolving fabrication issues is the evaluation of witness areas taken from fabricated components before testing the actual component. The witness material from these components allowed microstructural and mechanical testing to be performed and compared to the ideal, flat panel, conditions and data that are typical of basic characterization. This also allowed samples of similar design to be taken from components after 115 hours of combustion exposure. Testing consisted of tensile, double notch shear, ring burst, and thermal conductivity that sampled various regions of the components. The evaluation of the witness material allowed an understanding of the fabrication process, highlighting critical issues, in an early phase of the learning curve development of these configuration and material unique parts. Residual property testing, after exposure, showed if degradation of the material under actual service conditions was occurring. This paper will present the results of this critical testing. Evaluations that consider the degree of complexity of the fabricated part were established to relate *in situ* performance to that of flat panel based coupons. Nondestructive evaluation was used throughout the evaluation process. These results will also be discussed as an aid in understanding the test results.

Automated Acquisition and Analysis of Digital Radiographic Images

RICHARD POLAND, David Inmel, Boyd Howard, Randy Singer, and Bob Moore

Westinghouse Savannah River Company
Savannah River Site
P.O. Box 616
Aiken, SC 29808 USA
Phone: 803-725-1998
Fax: 803-725-1744
E-mail: richard.poland@srs.gov

Nondestructive Evaluation system specialists at the Savannah River Site have designed, built, and deployed a small-field-of-view, area-detector, lens-coupled, digital radiography imaging system. The fully automated imaging system is undergoing qualification tests for use on production components. Software routines for this system can automatically acquire, enhance, and diagnostically evaluate features of the item being radiographically imaged. Accuracy of the measurements obtained from the digitized image data is approximately 0.001 in. To date, there has been zero deviation in measurement repeatability. To achieve the desired accuracy, factors such as scintillation medium selection, x-ray source energy/physical properties, and geometrical sharpness issues were taken into consideration.

Resolution of these factors will be provided. Software to automatically acquire and analyze radiographic images will be described. The effects of specifically written filters that “defog” the high-density glass scintillator will be demonstrated.

Fabrication of Low-Cost, High-Temperature Composites for Rocket Propulsion Systems

MARK J. RIGALI, Manish Sutaria, Anthony C. Mulligan, and Ranji Vaidyanathan

Advanced Ceramics Research, Inc.
3292 E. Hemisphere Loop
Tucson, AZ 85706 USA
Phone: 520-573-6300
Fax: 520-573-2057
E-mail: r.vaidyanathan@acrtucson.com

Advanced Ceramics Research, Inc., (ACR) is currently developing two low-cost, flexible manufacturing processes to produce high-temperature composites with zirconium carbide (ZrC) matrices for use in current and future NASA and Department of Defense (DoD) propulsion applications. As a monolithic material, ZrC exhibits corrosion and ablation resistance at high temperatures. ZrC, however, does not possess the toughness and thermal shock resistance necessary to survive in many propulsion system applications. To enhance its toughness and thermal shock resistance, ACR is fabricating ZrC-based composites using two novel and low-cost composite fabrication techniques called Fibrous Monolith (FM) processing and Continuous Composite Co-extrusion (C^3) processing.

Fibrous Monolith processed composites are a new class of low-cost, bi- and multi-component structural ceramics. They exhibit mechanical properties similar to fiber composites or laminate structures, including very high fracture energies, damage tolerance, and graceful failure. Since they are monolithic powder-based composites, however, they can be manufactured by conventional powder processing techniques using inexpensive raw materials. In the FM process, an interpenetrating microstructure of elongated polycrystalline ‘cells’ of the matrix material (in this case, the high-temperature carbides and diborides) are separated and encapsulated by thin cell boundaries of a low shear strength material (BN, graphite, *etc*.) or a ductile material (W, Re, Mo, *etc*.) This interpenetrating microstructure imparts the necessary toughness and thermal shock resistance to the composite that is lacking in the monolithic carbides. The weak interface composites and many of the ductile interface composites exhibit fracture behavior similar to fiber reinforced ceramic composites, including the ability to fail in a non-catastrophic manner

C^3, based on the Fibrous Monolith processing technology, utilizes an innovative approach to produce continuous fiber reinforced composites. In the C^3 process, carbon fiber tow is passed through the center of a ceramic powder/thermoplastic binder feedstock during melt extrusion to produce a ‘green’ filament. The resulting filament is flexible, robust, and easily handled using traditional processing methods, *i.e.,* hand lay-up or filament winding; it is then pyrolyzed and hot pressed to produce dense parts. Although it was originally developed for the fabrication of ZrC and HfC carbon fiber composites for propulsion systems, the C^3 process promises to be applicable to the fabrication of a wide variety of other fiber-reinforced composites.

This paper highlights the mechanical and physical properties of the ZrC-based composites currently under development by ACR using the both the FM and C^3 fabrication processes. In addition, ACR is applying solid freeform fabrication (SFF) techniques to the production of these composite components currently being developed for several high-temperature DoD and NASA applications, including hot gas valves components, nozzles, thrust cells, and leading edges.

Electro Spark Alloy Processing for Aerospace Components

MICHAEL RILEY

Surface Treatment Technologies, Inc.
8600 Drumwood Road
Towson, MD 21286 USA
Phone: 410-828-5914
Fax: 410-828-1993
E-mail: mriley@stt-inc.com

Surface Treatment Technologies has employed the Electro Spark Alloying (ESA) process for three NASA hardware needs:

- Repair of pitting corrosion on Solid Rocket Booster (SRB) o-ring grooves
- Repair of 24K gold coatings on Space Shuttle engine components
- Formation of burn-resistant alloy coatings on oxygen delivery hardware.

The ESA process is a low-voltage arc welding technique in which an electrode deposits itself on a conductive metal or ceramic substrate. The resultant coating has the following key features:

- Full metallurgical bond to the substrate
- Nano-grain structure
- No heat-affected zone in the base alloy
- Capability of coating inside diameters and non-line-of-sight geometries.

Nano-grain coatings of metal, intermetallic, and ceramic layers have been formed on test specimens and subjected to relevant customer tests. Process information, metallurgical data, and test results from Phase I Small Business Innovation Research and NASA-related contracts will be presented.

Detection, Identification, and Quantification of Surface Contamination

M. MARTIN SZCZESNIAK, Michael Beecroft, and Phillip Mattison

Surface Optics Corporation
11555 Rancho Bernardo Road
San Diego, CA 92127
Phone: 858-675-7404
Fax: 858-675-2028

Even low levels of surface contamination can affect in a negative way physical properties of metal surfaces: adhesion, bonding, heat radiation. Detection of low contamination levels (below 1 microgram/cm^2) on large surfaces (more than 1 inch in diameter) is a challenge. A portable infrared reflectometer is applied to this application with a high level of success. The reflectometer covers the spectral region required to detect both the hydrocarbons and silicones. It is achieved with a Fourier Transform Infrared spectrometer. The sampling interface depends on the finish of the studied surface. The highly finished mirror-like surfaces can be analyzed with a specular reflectance accessory. The rough surfaces (grit-blasted) can be analyzed with the diffuse reflectance accessory. The reflectometer measures infrared spectra of suspected areas. The measurable infrared spectrum is an indication of surface contamination. The infrared spectra can be searched against standard or custom spectral libraries, which results in contaminant identification. The level of contamination can be predicted by applying calibration curves or chemometrics, PLS, CLS. The surface, which can not be accessed directly, can be swabbed and the residue extracted into the VSphere™. The VSphere™ is a patented accessory for the detection of nonvolatile residues. The minimum detection limits will be presented and discussed.

Quadruple Lap Shear Processing Evaluation

TONY N. THORNTON

Thiokol Propulsion
SEHO Operations
P.O. Box 707, M/S 200
Brigham City, UT 84302 USA
E-mail: THORNTN@thiokol.com

Thiokol, Science and Engineering Huntsville Operations (SEHO), has historically experienced unacceptable levels of variation in testing Quadruple Lap Shear (QLS) specimens utilized in the qualification of Reusable Solid Rocket Motor (RSRM) nozzle flex bearing materials. A test was conducted to enhance local Quadruple Lap Shear (QLS) processing and to define process sensitivities. A test matrix was designed to establish a baseline and introduce additional solvents or other variables. Variables included normal test plan delay times, pre-bond solvent hand-wipes and contaminants. Standard QLS hardware bonded with natural rubber was used for each test condition. Additionally, three replicates were performed for each condition. This paper will report the results and conclusions of this investigation.

Fatigue Crack Propagation Behaviour of Welded and Weld-Repaired 5083 Aluminum Alloy Joints

WEIDONG-WU

School of Aerospace and Mechanical Engineering
University College, University of New South Wales
Australian Defence Force Academy
Northcott Drive
Canberra ACT 2600 Australia
Phone: 61-2-6268-8275
Fax: 61-2-6268-8276
E-mail: w.wu@adfa.edu.au

Krishnakumar Shankar
School of Aerospace and Mechanical Engineering
University College, University of New South Wales
Australian Defence Force Academy
Northcott Drive
Canberra ACT 2600 Australia
Phone: 61-2-6268-8584
Fax: 61-2-6268-8276
E-mail: k.shankar@adfa.edu.au

Fatigue crack growth behaviour of 5083-H321 aluminum alloy plates in unwelded, welded, and weld-repaired conditions was investigated using single edge notched tension (SENT) specimens. Propagation rates for cracks in the heat-affected zone for welded specimens and the fusion zone for weld-repaired specimens were determined experimentally. The effects of weld residual stresses were taken into account by means of crack closure evaluation. Three-dimensional finite element models were employed to calculate stress intensity factors in the vicinity of the weldment, applying linear elastic fracture mechanics. Fatigue crack growth tests show that the weld residual stresses have a significant influence on the da/dN curves both for welded and weld-repaired plates. Metallurgical examination of the heat-affected zone indicates that the weld-repair process can significantly increase the grain size and the size of inner defects. The crack growth rates of weld-repaired plates are greater than those of the welded and plain materials.

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